Advancing Human-Computer Interaction for Space Exploration

SpaceCHI 2025, June 23–24, 2025,
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Preface

This volume contains the proceedings of the 4th SpaceCHI Conference on Advancing Human-Computer Interaction in Space Exploration, which was held at the European Astronaut Centre in Cologne, Germany on June 23–24, 2025.

SpaceCHI aims to bring together researchers and practitioners who draw on tools and methodologies from the field of Human-Computer Interaction (HCI), extending their use to the rapidly evolving domain of space exploration.

To understand the significance of HCI's potential in this new frontier, it is useful to reflect on its past impact. Following their emergence in the 1940s, electronic computers were typically confined to a handful of military facilities and government research centers, accessible to only narrow groups of users. It was not until the 1970s that computers began entering the mainstream consumer market, with the Altair 8800 personal computer released in 1975, and models from Apple, Commodore and IBM following soon after. HCI played an instrumental role in this transition, pioneering new interaction paradigms and embracing user-centered design principles, which ultimately enabled computers to permeate nearly every profession and aspect of modern society.

Space exploration is now undergoing a similar democratization. High costs and limited economic utility of space travel have historically made it a domain monopolized by a small number of governments. Today, innovations such as reusable rocketry are lowering barriers to entry, opening new markets, and fueling a global surge of private companies developing space-based technologies and services. Space exploration is, if you will, experiencing its own *Altair 8800 moment*. With a focus on designing and adapting technologies for diverse user needs, HCI is, once again, uniquely positioned to help lead this transformation.

The convergence of HCI and space exploration holds potential that extends far beyond shaping how humans interact with technologies in orbit. Space, with its distinct resource constraints, has consistently inspired ingenious design solutions that later reshaped our everyday life on Earth, giving rise to technologies such as digital photography, LED lighting, and renewable energy systems that now drive the green tech revolution.

SpaceCHI seeks to catalyze this potential by providing researchers from HCI-related disciplines a platform to share their work, explore future directions, and maximize the value of space technology for the many, not the few. Beyond advancing the exploration of distant worlds, its ultimate vision is thus to shape space innovations that create lasting benefits for life on our home planet, contributing to a better future for society as a whole.

While the first three editions of SpaceCHI were held as workshops at the MIT Media Lab in the USA, the 2025 edition marked a significant milestone, establishing SpaceCHI as a full conference and expanding its global presence by relocating to Europe. The move proved successful, with the conference growing over threefold from its previous iteration, attracting 70 attendees from diverse academic and industry backgrounds representing 19 nationalities. A total of 34 full papers were accepted, covering a broad spectrum of topics with significant real-world applicability, from additive manufacturing to AI-driven support systems.

This would, of course, not have been possible without the support and dedication of numerous individuals. We extend our gratitude to the MIT Media Lab team, particularly Joe Paradiso, Dava Newman, and Cody Paige, for endorsing our vision of hosting SpaceCHI 2025 in Europe. We are equally grateful to the European Space Agency for providing the opportunity to host the conference at the European Astronaut Centre, offering the perfect backdrop for the event. Special thanks go to Matthias Maurer, Frank De Winne, Andreas

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Mogensen, Aidan Cowley, and Lionel Ferra for their steadfast support, even amidst the challenges of German bureaucracy. We are also deeply indebted to our external reviewers, whose expertise ensured a high-quality conference program, and to our numerous colleagues in the HCI research community for their encouragement, guidance, and support throughout this journey. Finally, we would like to express our gratitude to all the authors who submitted their work to the conference – thank you for helping to lay the foundation for a community bold enough to imagine, design, and shape humanity's future among the stars.

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Human-AI Interaction in Space: Insights from a Mars Analog Mission with the Harmony Large Language Model

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Abstract

The operational complexities of space missions require reliable, context-aware technical assistance for astronauts, especially when technical expertise is not available onboard and communication with Earth is delayed or limited. In this context, Large Language Models present a promising opportunity to augment human capabilities. To this end, we present Harmony, a model designed to provide astronauts with real-time technical assistance, fostering human-AI collaboration during analog missions. We report empirical results from an experiment involving seven analog astronauts that evaluated their user experience with Harmony in both a conventional environment and an isolated, confined, and extreme physical setting at the Mars Desert Research Station over four sessions, and discuss how the Mars analog environment impacted their experience. Our findings reveal the extent to which human-AI interactions evolve across various user experience dimensions and suggest how Harmony can be further adapted to suit extreme environments, with a focus on SpaceCHI.

2012 ACM Subject Classification Applied computing → Aerospace; Computing methodologies → Machine learning approaches; Information systems → Language models; Applied computing → Computer-assisted instruction; Human-centered computing → Field studies; Human-centered computing → User studies; Human-centered computing → HCI design and evaluation methods; Human-centered computing → Graphical user interfaces

Keywords and phrases Extreme user experience, Human-AI interaction, Isolated-confined-extreme environment, Interaction design, Large Language Models, Mars Desert Research Station, Space mission, Technical assistance, Technical documentation, User experience

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Supplementary Material
Dataset (Spreadsheet with raw data, statistical and inferential analyses, and charts):
`https://www.kaggle.com/datasets/jeanvanderdonckt/dataset-spacechi2025-paper` [24]

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1 Introduction

Isolated, Confined, and Extreme (ICE) environments [2, 23] refer to settings with challenging constraints for their inhabitants, including psychological [28, 55], physical [30, 62], social [42], cognitive [29], and technological [3, 20], such as in space [23] or research stations [29]. In these environments, users are often isolated [2] or in small teams [26], typically confined in enclosed spaces for prolonged periods [27], and constrained by protective equipment.

These extreme conditions pose new challenges to the user experience (UX) of interacting with computer systems [55]. Although extensive research in Human-Computer Interaction (HCI) has covered traditional contexts of use [10, 13, 58], limited work has addressed UX challenges in ICE environments, where the extreme nature of the environment and the remote habitat [23] can significantly impact UX [53]. Under these constraints, astronauts must perform a wide range of tasks [4], from operating scientific instruments [61] to managing life-support systems [31], which require access to readily-available technical knowledge and documentation [14], not always present onboard. Moreover, astronauts cannot always count on real-time technical support from Earth given communications latency [5]. As Large Language Models (LLMs) can provide context-aware, real-time support for many tasks, such as self-scheduling [53] and operational exploration [21], they represent promising candidates for deployment as space mission assistants [5, 6]. This role makes them particularly relevant for ICE environments, where human-AI interaction remains underexplored.

In this paper, we examine how a mission at the Mars Desert Research Station, a representative ICE environment (Figure 1), affects the UX of analog astronauts interacting with Harmony, an LLM developed to provide technical assistance during space missions.

2 Related Work

Previous research about ICE environments has reported on individual attributes for contextual adaptation, including emotional stability, self-control, and task-oriented coping [2], while environmental design has led to recommendations involving display technology [17], personalization, and areas fostering privacy and socialization [55]. Moreover, environmental factors, such as sensory deprivation [62], sleep disturbances [64], and group dynamics, were shown to impact the functioning of ICE sojourners [57]. In this context, we relate to scientific literature at the intersection of HCI and space exploration with a focus on human-AI interaction.

2.1 HCI in Space

SpaceCHI [45, 46, 63] represents an initiative of the HCI community to investigate interactive computer systems in space, as a representative ICE environment, by "designing new types of interactive systems and computer interfaces that can support human living and working in



Figure 1 Photograph taken during our analog mission conducted at the Mars Desert Research Station, depicting an ICE environment with challenging physical constraints.

space and elsewhere in the solar system" [45, p. 1]. SpaceCHI emphasizes the diversity of topical coverage in space exploration requiring HCI knowledge and expertise [3], including software for crew collaboration [54], mission planning [63], human-system resilience and design for maintainability in space [37], participatory design for space systems engineering [40], food experience design for space travel [41], and examinations of the influence of extraterrestrial conditions on designing interactive systems [16, 17, 30].

However, the UX of interactions with computer systems in space has been briefly addressed in the scientific literature. For example, a self-scheduling application evaluated during a Mars analog mission [49] reported UX varying across pragmatic and hedonic dimensions, while Graphical User Interfaces (GUIs) for astronauts have started to be the subject of systematic UX design and assessment [19, 53]. Other research has looked at specific interactive computer technology in space. For example, interviews with astronauts and space experts regarding the capabilities of virtual environments facilitates user-centered approaches to operational performance [40]; MoonBuddy [7] consists of a voice-based VR system for extravehicular activities (EVA); Telemetron [16] is a musical instrument to play in ICE environments with low gravity; and Minerva [11] applies user-centered design for human exploration.

2.2 Human-AI Interaction in Space

AI technologies are increasingly utilized in space stations to enhance crew safety, productivity, and autonomy [15, 44]. Recent research has explored Human-AI interaction (HAI) in various contexts of use, including space applications. For example, a semi-formal representation of HAI using a set of interaction primitives and patterns was proposed in [56] with applications

to text summarization [8] and, at the International Space Station (ISS), AI models have proven valuable for data analysis and automation [43]. Specific AI technologies deployed at the ISS include NASA's Robonauts for assisting crew members and ATLAS for asteroid detection. AI has also been explored for providing medical aid to astronauts, such as in the absence of a doctor for the treatment of a fractured tibia [32], data analysis [43], and support for exploratory operations [21]. In this context, critical HAI aspects emphasize the need for mutual trust and reliability [44]. Since astronauts cannot access and manage the vast and diverse knowledge required to conduct space missions, AI assistants [5, 8, 12, 15, 21, 43, 44, 56] could help with finding answers to their questions in context. For example, Bensch et al. [5] combined information retrieval techniques, knowledge graphs, and Augmented Reality (AR) cues in their AI assistant for spaceflight operations [6]. These advancements enhance astronaut autonomy [4] while simultaneously addressing safety and assurance considerations [44], critical for practical implementations.

2.3 Summary

The recent interest of the HCI community in contributing to humanity's quest for reaching [34], working [31], and living [57] in ICE environments for space exploration [63], sets the context for our examination reported in this paper, where we focus on the UX of analog astronauts interacting with AI assistants in such environments. While proper UX design [22] can optimize the interaction between users and systems in conventional contexts, it requires careful and extensive examination in extraterrestrial environments [39]. Related research has primarily focused on technical aspects, such as hardware and software reliability or communications latency [45, 46, 63, 9] and, when tackling UX, on effectiveness and performance aspects. In this context, the need for research on how the specific challenges of ICE environments impact interactions and UX remains largely unaddressed [60]. Moreover, the growing interest in integrating AI in applications demands examination of the UX resulting from increasingly frequent human-AI interactions. Our work lies at the intersection of SpaceCHI, AI, and UX.

3 Implementation of Harmony

Harmony is an LLM designed to provide astronauts with technical assistance regarding tasks for which they do not necessarily have expertise or for which expertise is not readily available via remote communication with Earth. These tasks may include accessing system documentation, troubleshooting (diagnosing and resolving technical issues with spacecraft systems), experiment guidance (providing step-by-step instructions for scientific experiments), health monitoring (supporting medical procedures and monitoring crew well-being), mission planning (assisting in dynamic re-scheduling and optimizing resource utilization), and self-scheduling (self management of tasks); see details in [49, 53].

3.1 Software Architecture

The software architecture of Harmony is composed of four modules, each responsible for a specific task in the processing pipeline (Figure 2 and Table 1), as follows:

1. **Audio Capture**: Audio input is captured using a microphone and activated with a mouse click acting as a push-to-talk control. This interaction simplifies hardware requirements and allows for flexible input in low gravity conditions [17].
2. **Speech-to-Text Transcription**: The OpenAI Whisper ASR model, a robust and accurate English speech recognition engine, runs locally and transcribes the astronaut's question into text without requiring an Internet connection.

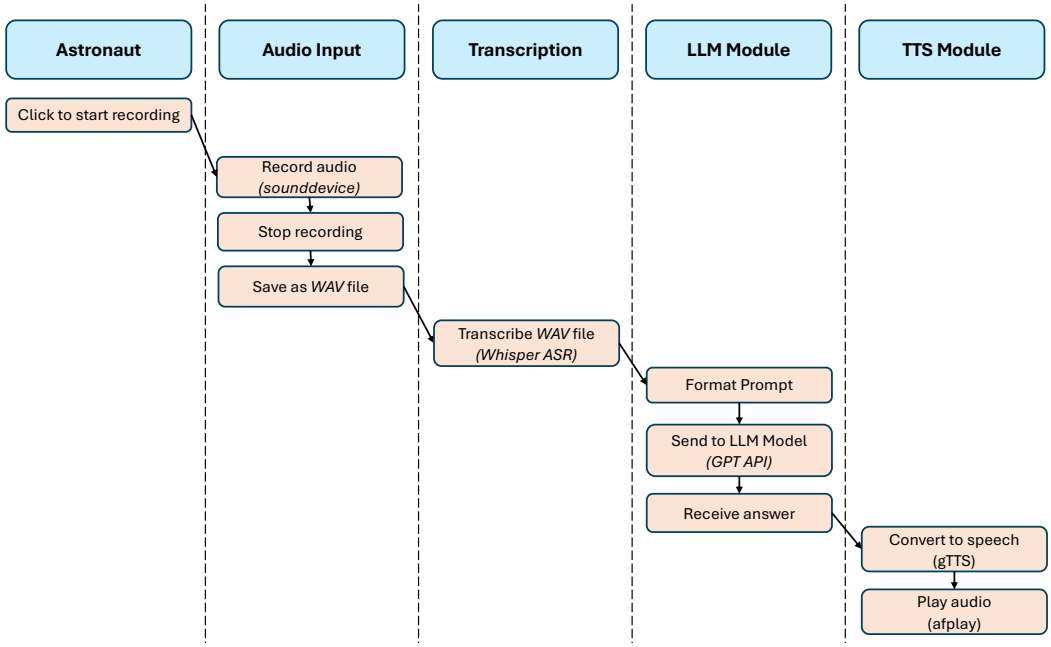

Figure 2 The UML Activity Diagram of Harmony.

Table 1 Overview of the software modules implemented for voice-based interaction in Harmony.

Module	Library/Tool	Function
Audio Recording	`sounddevice`, `pynput`	Capture of voice input via click trigger
Speech-to-Text	`Whisper (base)`	Transcription of recorded audio into text
LLM Interaction	`OpenAI API (GPT-3.5-turbo)`	Generating responses based on transcription
Text-to-Speech	`gTTS (Google Text-to-Speech)`	Conversion of LLM response into vocal output
Audio Playback	`os.system + afplay`	Local playback of the generated audio

3. **Query Generation and Answering**: The transcribed question is processed and sent to an LLM based on GPT-3.5-turbo, which formulates a concise, mission-adapted response. This module operates either locally, with a fine-tuned model, or via the Google Cloud API when a communication link with Earth is available.[2]

4. **Text-to-Speech Response**: The generated answer is converted back into audio using the Google Text-to-Speech gTTS engine, a Python library and Command-Line Interface tool to interface with gTTS API, allowing astronauts to receive direct vocal feedback.

This modular architecture ensures that each component can be independently updated or adapted based on mission requirements. For example, the LLM backend could be swapped for an onboard model in deep space scenarios with communication latency, while a more advanced Text-To-Speech module, such as Tacotron 2 or Coqui TTS, added to the architecture to improve perceived naturalness of voice-based feedback.

[2] An LLM capable of running locally on the onboard computer was initially implemented but, during the mission, we considered an LLM based directly on GPT-3.5-turbo for faster and more relevant responses.

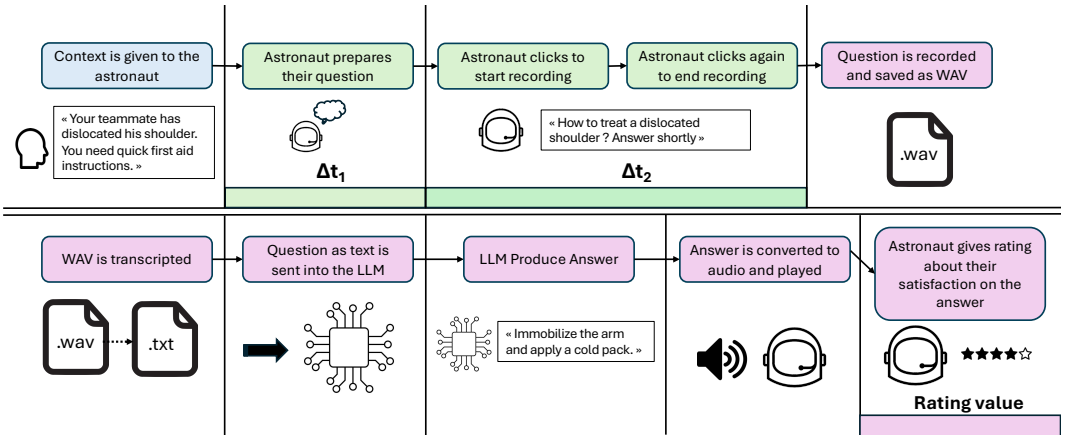

Figure 3 A system walkthrough of Harmony; see Figure 4 for an example.

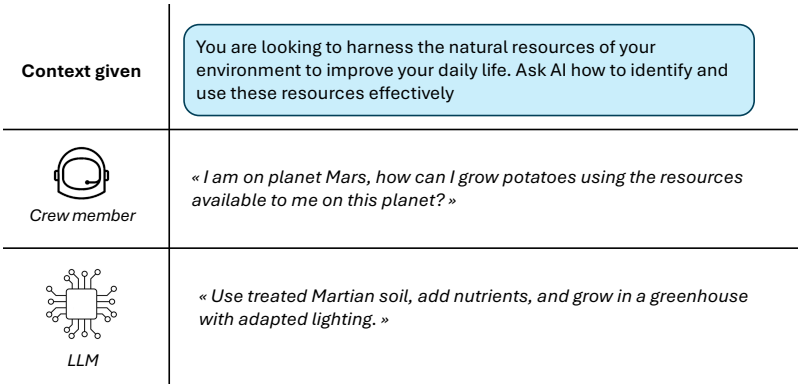

Figure 4 Example of an interaction with Harmony.

3.2 System Walkthrough

To foster trust and reliability [44], Harmony employs a conversational user interface [48] designed based on the following principles [1]: *transparency* to explain the reasoning behind the provided suggestions to ensure astronaut confidence, *adaptability* to personalize responses based on individual crew preferences and roles, and *error management* to detect and mitigate inaccuracies through validation mechanisms, e.g., reinforcing or deforcing an answer. Figure 3 presents a concrete system walkthrough illustrating how Harmony operates in a real-world scenario. This step-by-step description follows the typical interaction between astronauts and Harmony, from voice input to a vocal response: a context of is first provided to the analog astronaut with a goal to achieve; subsequently, the astronaut formulates mentally a question corresponding to the goal (Δt_1); the astronaut enters the question with voice input (Δt_2); the question is transcripted and sent to the LLM to produce an answer that is converted to audio to preserve the conversational style; lastly, the astronaut rates their satisfaction regarding the provided answer to improve the LLM training.

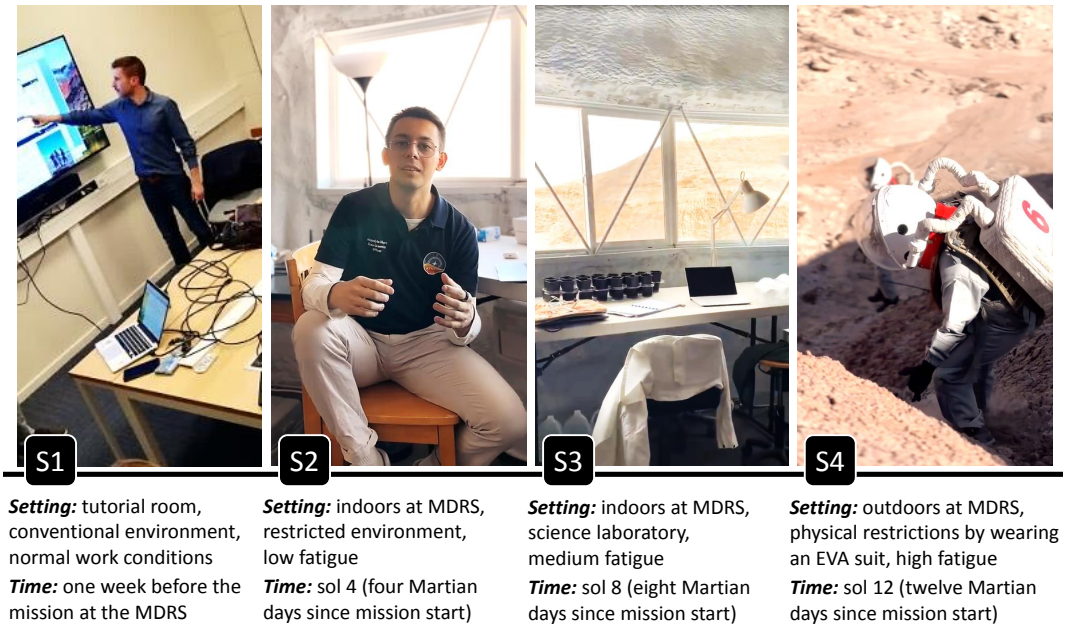

Figure 5 Timeline of the experiment with four stages taking place before (S1) and during the analog mission (S2 to S4) at the MDRS.

4 Experiment

This section presents the experiment conducted to assess the UX of Harmony; see Figure 5.

4.1 Location

The experiment took place at the Mars Desert Research Station (MDRS), a simulated Mars-inhabited environment in Hanksville, UT, USA, serving as an international research facility for studying human factors and conducting experiments for future Mars missions [18, 47]. MDRS is composed of several modules, including the habitat, the EVA preparation room, and the science dome with a science laboratory; see Figure 5 and a 3D navigation in VR.

4.2 Participants

The experiment was carried out with a crew of seven analog astronauts (four women and three men), aged between 21 and 31 years (M=24.75, SD=2.63), who spent two weeks at the MDRS with multiple daily reporting and protocols. Participants had different backgrounds, such as astronomy, biology, chemistry, computer science, geology, and engineering.

4.3 Stimuli

Based on [49, 53], we defined a series of contexts of use, each associated with a situation and a corresponding question, as follows (see Figure 4 for an example):

- Q_1. *Medical assistance in case of injury*: Your teammate has just dislocated their shoulder on a mission. Formulate a question to the AI to learn how to react and what first aid measures to apply.

- Q_2. *Cooking in space with dehydrated products*: You want to prepare pancakes using only dehydrated ingredients. Ask the AI for a suitable recipe.
- Q_3. *Entertainment*: You want the AI to play the role of a general knowledge quiz host. Formulate a question so that it suggests an interesting challenge.
- Q_4. *Communication with a foreign colleague*: You meet a foreign colleague and have difficulty communicating with them. Ask the AI for translation or communication tips.
- Q_5. *Recipe ideas with limited resources*: You have harvested basil and you want to use it to prepare your meal. Ask the AI for two or three dishes ideas.
- Q_6. *Language learning in your spare time*: You want to learn a few words in a new language in your spare time. Ask the AI a question, which will teach you useful vocabulary.
- Q_7. *Physical exercise in a confined space*: You are confined to a small space for a long time and want to keep fit. Ask the AI for a physical exercise routine that can be performed without specialized equipment.
- Q_8. *Project management skills development*: You want to improve your project management skills in your spare time. Ask the AI for resources or a learning plan.
- Q_9. *Using natural resources*: You are looking to harness the natural resources of your environment. Ask the AI how to identify and use these resources effectively.
- Q_{10}. *Team building*: To strengthen team cohesion, you want to organize a team-building game. Ask the AI a question to get ideas tailored to your mission.
- Q_{11}. *Water purification in the event of a technical problem*: A technical problem affects your water supply. Ask the AI what alternative purification methods you can implement.
- Q_{12}. *Night navigation without instruments*: You are lost without a compass and want to find your way using the constellations. Ask the AI a question to learn the basics of astronomical navigation.
- Q_{13}. *Setting up a recycling or composting system*: With limited resources, you want to set up a small recycling or composting system. Ask the AI for advice on how to do it.
- Q_{14}. *Stress management and relaxation*: You are experiencing a lot of stress and would like to practice a relaxation technique. Ask the AI for instructions for a relaxation session.
- Q_{15}. *Recognizing and treating hypothermia*: You are confronted with extremely cold conditions and suspect hypothermia. Ask the AI how to identify symptoms and what treatment to apply with the available means.

4.4 Measures

To evaluate UX, we relied on the UEQ+ method, a modular extension of the User Experience Questionnaire (UEQ) [51, 52], which covers both pragmatic and hedonic UX dimensions and is supported by analysis instruments and published norms [38] for interpreting results [25]. Based on prior work [59, 60], we selected the following UX dimensions for our experiment:

- *Attractiveness*: The overall impression concerning Harmony. Do users like it or not?
- *Efficiency*: The impression that tasks can be successfully performed with Harmony without unnecessary effort. Can users solve their tasks efficiently?
- *Perspicuity*: The impression that Harmony is easy to learn how to use. To what extent do users find Harmony easy to learn?
- *Dependability*: The impression to be in control of the interaction with Harmony. To what extent does Harmony give users the feeling that they are in control of the interaction?
- *Stimulation*: The impression that Harmony is interesting and fun to use. Do users find Harmony exciting and motivating?
- *Novelty*: The impression that Harmony is creative and original. To what extent do users appreciate Harmony as creative? Does it catch their interest?

- *Adaptability*: The impression that Harmony can be easily adapted to personal preferences or working styles. To what extent does Harmony appear adaptable?
- *Trust*: The impression of the users that their data are safe with Harmony and not misused to harm them. Do users feel confident that their data is secure and handled appropriately?
- *Usefulness*: The impression that using Harmony is beneficial. Do users perceive any advantages in interacting with Harmony?
- *Value*: The impression that Harmony looks professional and valuable. To what extent does the design of Harmony convey a sense of professionalism and quality?
- *Visual aesthetics*: The impression that the graphical interface of Harmony looks beautiful and appealing. Do users find the visual design of Harmony attractive and engaging?
- *Intuitive use*: The impression that Harmony can be used immediately without any training or help. Can users start using it right away without needing help or instruction?
- *Trustworthiness of content*: The impression that the information provided by Harmony is of good quality and reliable. To what extent is the information provided by Harmony perceived as accurate and trustworthy?

We refer to UEQ+ [51, 52, 38, 25] for further details about these dimensions. Following prior research [60, 59], we report for each dimension the Scale-Mean-Score (SMS) as the average score obtained on all its subscales, ranging from -3 (negative experience) to $+3$ (positive experience), and the Scale-Mean-Importance (SMI), representing the average weight of importance of a given UX dimension; see Vanderdonckt et al. [59] for calculation details. Furthermore, to compare the scale of a target, *e.g.*, an extreme condition such as Mars, to the corresponding scale of a baseline such as Earth, we use:

$$\text{Scale-Mean-Ratio} = \frac{\text{SMS } (target)}{\text{SMS } (baseline)} \tag{1}$$

$$\text{Scale-Importance-Ratio} = \frac{\text{SMI } (target)}{\text{SMI } (baseline)} \tag{2}$$

Participants' answers were computed with the UEQ data analysis tool and interpreted according to Schrepp et al.'s [52] recommendation: "the standard interpretation of the scale means that values between -0.8 and 0.8 represent a neutral evaluation of the corresponding scale, values superior to 0.8 represent a positive evaluation."

We also measured:

- Quality-Score: a numerical variable representing the perceived quality of the answer provided by Harmony to the question prompted, from 0 (failure) to 1 (lowest quality) to 5 (highest quality for complete and correct answers).
- Success-Factor: a numerical variable defined as the number of iterations needed to complete a task successfully.
- Thinking-Time: a numerical variable defined as the time elapsed between the moment when the task was presented and the moment when the participant started the interaction with Harmony, measured in seconds with a stopwatch (Δt_1 in Figure 3).
- Production-Time: a numerical variable defined as the time needed to formulate and record the question, measured in seconds with a stopwatch (Δt_2 in Figure 3).
- Confidence: an integer variable expressing the degree of confidence attributed to the answer provided by Harmony for the given context, ranging from 1% (no confidence) to 100% (maximum confidence).

4.5 Apparatus and Tasks

Harmony ran on an Apple MacBook Air with a 13" Retina screen (2560×1600 pixels), 8-core 3.2 GHz CPU, 8 GB RAM, and 256 GB SSD. The Apple AirPods Pro 2 were used for audio input and output. We devised four tasks to be carried out in the experiment:

- A *discovery task*, in which the participants received a tutorial on using Harmony, lasting between 5 and 15 minutes, and then interacted freely for another 10 to 15 minutes.
- A *practice task*, in which the participants were instructed to perform a representative task with Harmony to become familiar with it, lasting about 20 minutes.
- A *domain task*, in which the participants received five stimuli (Q_1 to Q_5, Q_6 to Q_{10}, and Q_{11} to Q_{15} in random order). We suggested, but not imposed, a time limit of 10 minutes.
- An *evaluation task*, in which the participants filled out the UEQ+ questionnaire.

The discovery and practice tasks were performed once before the mission in a dedicated tutorial room (see Figure 5, left). The domain and evaluation tasks were performed four times during four subsequent sessions, as follows: a first session S1 one week before the mission in the tutorial room (Figure 5, left), a second session S2 after four Mars days[3](Sol 4) in the science laboratory (Figure 5, middle left), a third session S3 after eight Mars days (Sol 8) outside the station and involving light equipment (Figure 5, middle right), and a fourth session S4 after twelve Mars days (Sol 12) outside the station involving heavy equipment, stress, and high fatigue due to the ICE environment and continuous exposure to its constraints (Figure 5, right).

5 Results and Discussion

5.1 The User Experience of Interacting with Harmony

The panel charts in Figure 6 present the Scale-Mean-Scores (SMS) and Scale-Mean-Importance (SMI) for the various UX dimensions. Overall, all scores fall into the positive experience zone, above the 0.8 threshold. This phenomenon is rarely observed in such evaluations [50], which suggests that participants assessed their interactions with Harmony positively throughout the study. While the score range remains mostly similar across sessions, the scales receiving the minimum and maximum scores differ: *Visual aesthetics* (M=1.25, SD=1.02) and *Attractiveness* (M=2.18, SD=0.71) define the range in S3 whereas *Adaptability* (M=1.32, SD=1.39), *Attractiveness* (M=2.18, SD=0.80), and *Stimulation* (M=2.18, SD=0.66) in S4. The following trends can be distinguished for the observed UX:

- *V-shaped curves* undergo a noticeable drop, represented by a local minimum of the SMS starting in the first session on Mars, then gradually rising to S4; see *Perspicuity*, *Trust*, *Value*, and *Intuitive use* ($\frac{4}{13}$=31%). For example, *Value* started from a mean score of M=1.82 (SD=0.76) in S2 and reached M=1.79 (SD=0.86) in S4.
- *Inverted V-shaped curves* represent the opposite trend with a local maximum and ending with a lower score; see *Efficiency* ($\frac{1}{13}$=8%).
- *Overall upward trends* progressively increase from the first to the last evaluation session; see *Attractiveness*, *Stimulation*, and *Visual aesthetics* ($\frac{3}{13}$=23%). For example, *Stimulation* increased from S2 (M=1.64, SD=1.04) to S4 (M=2.18, SD=0.66).

[3] A Mars-day, or a *Sol*, constitutes a solar day on Mars, *i.e.*, the apparent interval between two successive returns of the Sun to the same meridian as seen by an observer on Mars, which is approximately 24 hours, 39 minutes, and 35 seconds on Earth.

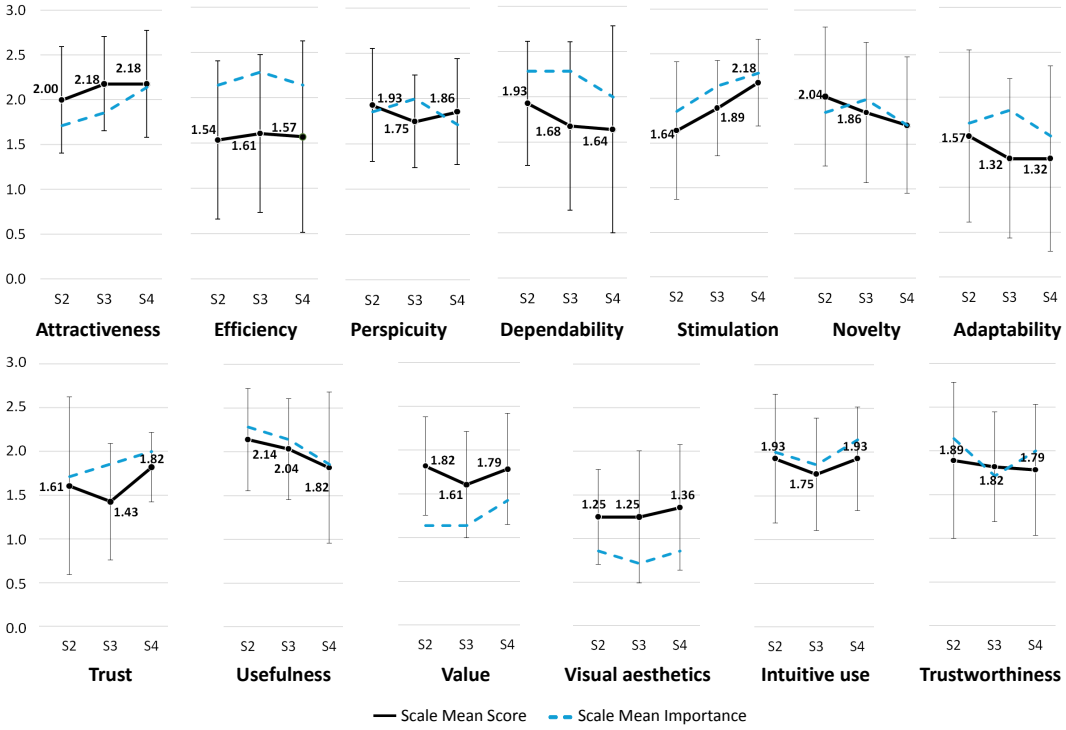

Figure 6 The UX dimensions evaluated for Harmony, showing mean scale scores (solid lines) and scale importance scores (dotted lines) across the mission sessions. The error bars show 95% CIs.

- *Overall downward trends* progressively decrease from the first to the last evaluation session; see *Dependability*, *Novelty*, *Adaptability*, *Usefulness*, and *Trustworthiness* ($\frac{5}{13}$=38%).

These results should be interpreted based on the importance attributed by the participants, measured with the Scale-Mean-Importance (SMI) scores, as detailed below:

- *V-shaped curves* ($\frac{4}{13}$=31%) for *Value*, *Visual Aesthetics*, *Intuitive use*, and *Trustworthiness*.
- *Inverted V-shaped curves* ($\frac{5}{13}$=38%) for *Efficiency*, *Perspicuity*, *Dependability*, *Adaptability*, and *Novelty*.
- *Upward curves* ($\frac{3}{13}$=23%) for *Attractiveness*, *Stimulation*, and *Trust*.
- *Downward curve* ($\frac{1}{13}$=8%) for *Usefulness*.

5.2 Perceptions of Harmony's Answers

Figure 7 shows Quality-Score evaluations of the answers provided by Harmony. A one-way ANOVA revealed a statistically significant difference across the conditions ($F_{14,90}$=2.22, $^{*}p$=.013) with a large effect size (η^2=0.26). Tukey's HSD Test for multiple comparisons found that the mean value of Quality-Score was significantly different between Q_2 and Q_6 (p=.027, 95% CI=[0.16, 5.55]) and between Q_6 and Q_{13} (p=.046, 95% CI=[0.02, 5.40]). Wilcoxon signed-rank tests among the group of five questions in each session (Sol 4, Sol 8, and Sol 12) revealed Sol 4 and Sol 8 significantly different (z=1.90, p=.028, r=.22).

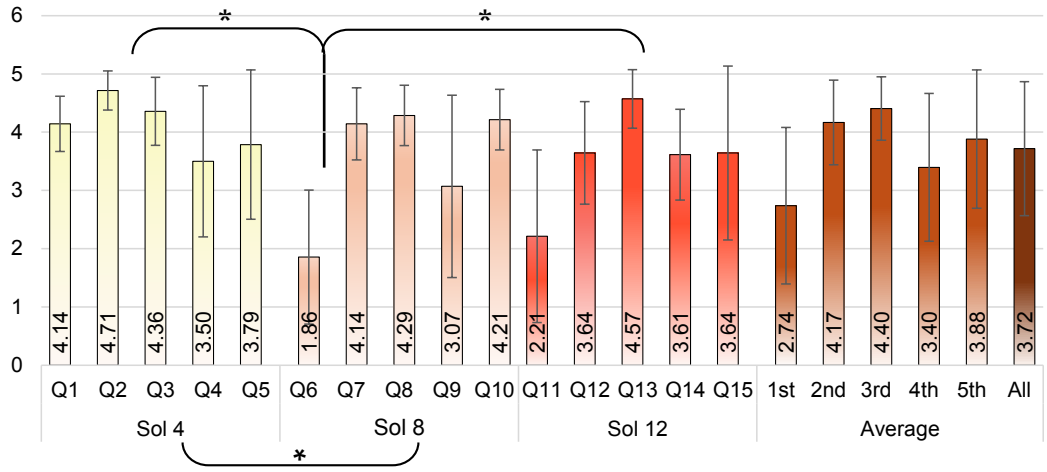

Figure 7 Quality scores of the answers provided by Harmony, from 0 (failure) to 1 (lowest quality) to 5 (highest quality). Error bars show 95% CIs; significance levels are reported at p=.05*.

5.3 User Performance

Figure 8, top shows the average Thinking-Time participants needed for the various tasks, with no statistically significant difference ($F_{14,90}$=1.01, p=.056, *n.s.*). However, when we considered the total Thinking-Time per session, a Wilcoxon signed-rank test revealed that the Sol 4 and Sol 12 conditions were significantly different (z=2.58, p=.0049) with a medium effect size (r=.31), as well as Sol 8 and Sol 12 (z=2.62, p=.0043). This finding suggests that the participants benefited from a learning effect. We did not find any other significant difference between the other sessions and between the five orders of questions, suggesting that the participants needed a similar time to address questions. Figure 8, right shows the average Production-Time participants needed for the various tasks. A one-way ANOVA revealed a statistically significant difference across the conditions ($F_{14,90}$=4.32, $p\leq$.001) with a medium effect size (η^2=.40). The average production time significantly increased from one session to the next ($F_{2,102}$=14.11, $p\leq$.001) with a small effect size (η^2=.22). This result suggests that the participants were progressively more careful in how they entered the vocal command to implement the interaction with Harmony.

Figure 9, left shows how many trials were performed for each question: on average, the questions were assessed as satisfying after the first trial (71%), the second trial (14%), and the third trial (15%), respectively. The answers provided by Harmony to Q_2, Q_7, Q_8, and Q_{12} were judged satisfactory during the first trial mainly due to our participants' familiarity with the question domain (*e.g.*, food, management). Figure 9, right shows the Confidence evaluations of the answers provided by Harmony, ranging from a minimum of 57.97% for Q_3 to a maximum of 71.14% for Q_{13}. The mean of 65.61% suggests that the participants had moderate confidence in the answers provided by Harmony, probably due to a lack of traceability and explanation, in line with the Trust scores. Participants repeatedly expressed doubts about the system's answers, *e.g.*, Q_{11} about water purification and Q_{15} in medicine, except in the case of participants whose area of expertise was relevant. Figure 10 shows the average number of words per question with Q_{13} and Q_{14}, Q_3 and Q_5 standing out with the highest (30) and the lowest number of words (12), respectively.

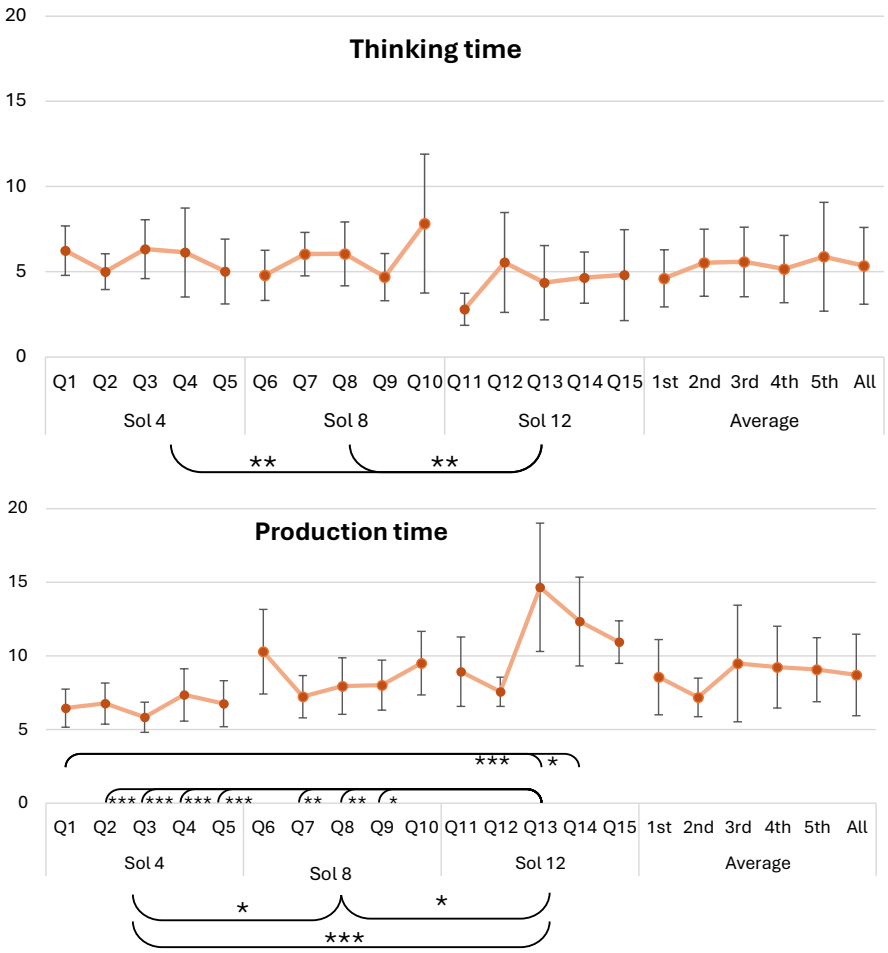

Figure 8 Thinking time (top) and production time (bottom) of the questions asked by the analog astronauts. Error bars show 95% CIs; significance levels are $p \leq .05^{*}$, $p \leq .01^{**}$, and $p \leq .001^{***}$.

5.4 Summary

Table 2 provides a summary of the main UX trends identified in our experiment:

- *Attractiveness*: The value and importance associated with this pragmatic dimension increased over the evaluation sessions, suggesting that participants developed a more favorable overall impression and came to recognize the significance of this dimension.
- *Efficiency*: This pragmatic dimension was the most affected by the ICE conditions, which was an expected result since performance represents the primary criterion in such contexts [34, 35, 36], while its importance remained consistent across sessions.
- *Perspicuity*: This dimension showed a decline in both value and importance across the sessions, though not significantly. This finding suggests that further attention is needed to ensure transparency of system functionality for increased learnability and ease of use.
- *Dependability*: This pragmatic dimension revealed the greatest decline in value after *Efficiency,* including in terms of participants' perceived importance. Moreover, participants' sense of control over the LLM decreased over time, likely due to the similarity of the responses received and the lack of variation in the level of detail.

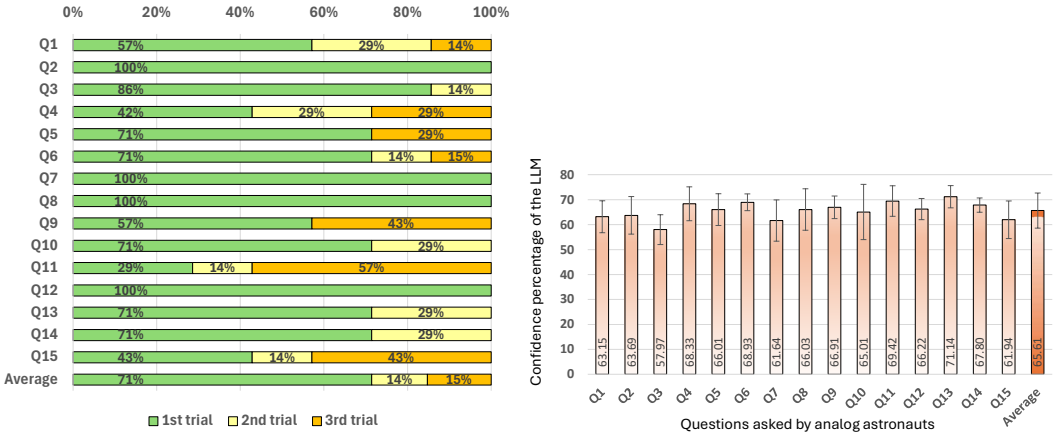

Figure 9 Trials per question (left, see Section 4.3) and CONFIDENCE levels (right).

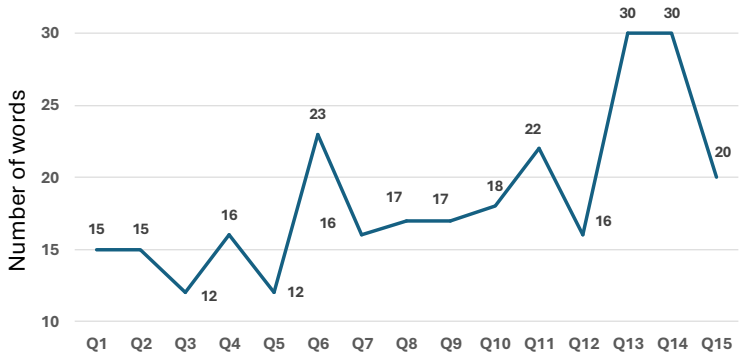

Figure 10 Number of words per question (Q_1 to Q_{15}).

- *Stimulation*: This hedonic dimension revealed a growing importance surpassing what is typically observed in a conventional Earth-like setting. Stimulation was strongly affected from the beginning to the end, where participants reported feeling increasingly stimulated when using the LLM, due to the growing importance also felt in terms of *Value*.
- *Novelty*: The scores of this dimension decreased progressively across the evaluation sessions as participants become more accustomed to Harmony, resulting in a reduction in both its perceived value and importance.
- *Adaptability*: While participants appreciated the consistency of the answers, they expressed concerns that Harmony did not provide any means to adapt responses to their individual needs, preferences, or level of expertise. For less experienced users, responses could benefit from progressively increasing levels of detail according to the request, whereas the more experienced participants preferred concise summaries. These findings indicate a clear need for adaptive response mechanisms according to the context of the question, including its urgent or safety-critical nature.
- *Trust*: Participants reported feeling increasingly secure when using the system, mainly due to the quality of the responses. Confidence was also reinforced by the reduced number of trials, an observation consistent with findings reported in previous work [44].
- *Usefulness*: This dimension, initially recognized for its benefits, declines over the evaluation sessions, a finding that highlights the need for strategies to maintain perceived usefulness over time.

Table 2 Evolution of UX scales over sessions: $\simeq$= ratio similar to Earth, $<$ = ratio inferior to Earth, $>$ = ratio superior to Earth, $\ll$ = ratio largely inferior to Earth, and $\gg$ = ratio largely superior to Earth. SMS = scale mean score, SMI = scale mean importance.

Scale	SMS	SMI	Scale	SMS	SMI
Attractiveness	$\gg$	$\gg$	*Trust*	$\gg$	$\gg$
Efficiency	$\ll$	$\simeq$	*Usefulness*	$\ll$	$\ll$
Perspicuity	$<$	$<$	*Value*	$\simeq$	$\gg$
Dependability	$\ll$	$\ll$	*Visual Aesthetics*	$>$	$\simeq$
Stimulation	$\gg$	$\gg$	*Intuitive Use*	$\simeq$	$>$
Novelty	$\ll$	$<$	*Trustworthiness*	$<$	$<$
Adaptability	$\ll$	$\ll$			

- *Visual aesthetics*: This dimension became increasingly valued over the sessions with a stable level of perceived importance. As such, it does not need major changes.
- *Intuitive use*: This dimension remained constant, but warrants further attention due to its growing perceived importance.
- *Trustworthiness*: This dimension requires increased attention as participants perceived it as deteriorating over sessions, casting doubt on Harmony's interaction capabilities.

The dimensions requiring significant improvement are *Efficiency*, *Dependability*, *Adaptability*, *Usefulness*, and *Trustworthiness* (the latter to a lesser extent since it is somewhat compensated by *Trust*). In contrast, *Attractiveness*, *Stimulation*, *Trust*, and *Visual Aesthetics* showed positive development over time, despite the ICE conditions becoming more constraining, and do not warrant immediate action. Lastly, *Perspicuity* and *Trustworthiness* could be slightly improved, whereas *Value* and *Intuitive Use* received consistently positive evaluations.

6 Conclusion and Future Work

We reported results from an experiment involving seven analog astronauts who evaluated their user experience of interacting with Harmony, an LLM designed for real-time technical assistance in ICE environments. We identified the UX dimensions that require improvement, others necessitating optional enhancements, while others were consistently rated positively across multiple evaluations. In this context, LLMs have the potential to revolutionize astronaut assistance by providing intelligent, context-aware support during space missions. While technical challenges remain, continued research and development have the potential to significantly enhance mission efficiency, safety, and success. For example, designing an LLM that supports mental well-being in ICE environments, *e.g.*, through emotional intelligence and personalized interactions, should help enhance *Efficiency* and *Adaptability* through personalized LLM behavior and an adapted tone for long-term engagement. The LLM's responses should be transparent and easy to understand for more trusting and rewarding human-AI collaboration, which requires sensing the context of use and employing techniques to optimize LLM processing. Moreover, collaboration between humans and AI represents a critical step toward sustainable and autonomous space exploration. Future work can compare various adaptation techniques to address the UX dimensions necessitating improvement, particularly by considering alternative interaction modalities [59]. In our experiment, we tested only a graphical user interface with voice-based input, excluding other interaction modalities, such as gesture commands for hands-free operation and haptic feedback when astronauts wear gloves [33], which can be explored in future work.

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Best Practices in CubeSat Control Software Development: A Case Study of the SAGE Mission

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Abstract

The increasing complexity of CubeSat missions necessitates mission control software that is both efficient and user-friendly. This paper describes the design and implementation of a multi-mission CubeSat user interface for the SAGE Mission, a student-led CubeSat program. The system includes a web-based interface that provides telemetry visualisation, automated job scheduling, and real-time monitoring. Its architecture is designed to be modular, scalable, and accessible, allowing integration with multiple ground stations and support for various mission configurations. Input from stakeholders played a crucial role in shaping the interface through user evaluations, expert feedback, and digital twin simulations. Our findings highlight the significance of user-centred design in space mission software, particularly in educational and resource-constrained settings. The CubeSat SAGE mission control software enhances the accessibility of multi-mission operations and offers valuable insights into the future of space system interfaces.

2012 ACM Subject Classification Human-centered computing → Interactive systems and tools

Keywords and phrases Automated mission operations, CubeSat operations, Ground segment software, Mission control software (MCS), Multi-mission operations, Satellite mission planning, SpaceCHI Telemetry data visualisation, User interface design

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1 Introduction & Motivation

CubeSats have revolutionised space access through their compact size and cost-effectiveness, enabling broader participation in space exploration [18]. However, managing multiple CubeSat missions introduces coordination and resource management challenges [9]. An efficient mission control software (MCS) with a well-designed user interface (UI) is essential for mission success.

Effective mission control software must provide robust technical functionality and ensure usability, trust, and efficiency in high-stakes environments. The SAGE mission, a student-led CubeSat mission, incorporates those design principles that enhance operator interaction, automate routine tasks, and mitigate cognitive load, ultimately improving mission efficiency and reliability.

This paper presents the design and implementation of a multi-mission CubeSat control software for the SAGE mission. The project addresses challenges in student-led missions, including high team turnover and limited experience compared to commercial operations.

SAGE is a 3-Unit (3U) CubeSat developed by ARIS. CubeSats are nanosatellites with basic units of $10 \times 10 \times 10$ cm, serving as low-cost alternatives to larger spacecraft [18]. One unit houses a biological payload, while the remaining two accommodate spacecraft systems. The mission objectives include providing an educational satellite platform in space, studying human cell ageing in microgravity, operating an amateur radio and custom GNSS equipment,


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Figure 1 The multi-mission CubeSat control software for the SAGE mission in use.

and testing a custom RISC-V ASIC developed at the Integrated Systems Laboratory at ETH Zurich. The mission will be launched into a sun-synchronous Low Earth Orbit by a U.S.-based launch provider in 2026. The following teams are contributing to mission success and were involved in the design of the SAGE MCS:

- **Thermal Control and Structures (TC-STR):** Ensures the CubeSat can withstand launch and space conditions, provides mounting for other subsystems, and maintains satellite temperature within operating limits.
- **Biological Payload (PAY):** Investigates human cell ageing by hosting the first human cell culture in space.
- **Electrical Power System (EPS):** Generates, stores, and provides power using solar panels, a battery pack, and a power distribution module.
- **Communication System (COM):** Enables data reception, command transmission, and health status monitoring.
- **Attitude Determination and Control System (ADCS):** Assesses, monitors, and adjusts the satellite's attitude using sensors, actuators, and state estimation software.
- **On-Board Computer (OBC):** Manages and processes tasks across subsystems, ensures satellite health, and provides local data storage.
- **Mission Operations (MOPS):** Operates the satellite from a Mission Operations Center in Zurich, including orbit determination, health monitoring, conducting experiments, and addressing anomalies.

CubeSat operations are divided into data retrieval and job scheduling, ensuring mission objectives are met. Data retrieval involves acquiring telemetry and payload data from the satellite. Raw data packets are received via ground station antennas, decoded, processed, and stored in a central database for analysis. Data integrity and redundancy are crucial for anomaly detection and mission performance assessment.

Job scheduling pertains to defining, verifying, and executing commands to control satellite operations. Users define jobs via a UI, which is then verified using a digital twin simulation. Verified jobs are uplinked to the CubeSat and executed at the scheduled time, with each step logged for traceability and troubleshooting.

2 Related Work

The development and maintenance of operations centres for satellite missions have been the subject of past research. Traditional satellite operations centres are often designed for single missions and may not provide an efficient foundation for managing multiple concurrent (CubeSat) satellite missions. This has led to a shift towards the adoption of multi-mission software solutions in recent years.

To support the simultaneous management of multiple satellite missions, the concept of a Multi-Mission Operations Centre (MMOC) has been introduced. In collaboration with European national space agencies, the European Space Agency (ESA) developed the European Ground Systems Common Core (EGS-CC)[1], providing a shared infrastructure to facilitate the implementation of different missions [15, 2]. Similarly, NASA's Multi-Mission Operations Center (MMOC)[2] and the Advanced Multi-Mission Operations Service (AMMOS)[3] offer frameworks that enable the efficient operation of multiple missions using shared resources [9].

CubeSat missions present special operational requirements due to their inherent resource limitations and relatively short mission lifespans [10]. Traditionally, space missions have focused on the development of high-cost, large-scale satellites, but there has been a growing trend towards smaller satellite systems. CubeSats, particularly, have gained popularity among educational institutions, space agencies, and industry stakeholders due to their versatility and rapid development cycles [1].

At SpaceCHI, although not the core focus, related aspects of crew autonomy and space system development have been discussed in previous editions of the conference. Already in 2007, Huang et al. [5] explored the use of large interactive displays for workgroup collaboration, noting that while many systems have been tested in labs, they face challenges when deployed in real-world settings. Their study examines the adoption of NASA MERBoards during the Mars Exploration Rover missions, identifying deployment challenges external to the system design, and discusses how these issues apply to the broader use of shared ubiquitous computing technologies. More recently, Zheng et al. [21] emphasise the growing need for crew autonomy during long-duration missions, particularly in mission planning, due to the communication delays inherent in deep-space exploration. They propose a mixed-initiative approach where a computer assists in managing complex tasks like constraint handling while still allowing astronauts to retain control. The Playbook tool, designed for this purpose, addresses these challenges with its innovative scheduling capabilities, supporting autonomous crew planning.

[1] http://www.egscc.esa.int/
[2] https://www.nasa.gov/mmoc/
[3] https://ammos.nasa.gov/

Similarly, Nilsson et al. [13] critique traditional analogue environments for space system development, highlighting their high costs and limited participation. To counter these limitations, they are developing a mixed-reality testbed that combines physical mockups with digital extensions. This more accessible and cost-effective approach aims to facilitate participatory design and rapid prototyping, ensuring that the diverse future users of space systems can contribute to their development.

Building on these concepts of autonomy and more flexible and modular system design, Karasinski [6] stresses the necessity of enhanced crew autonomy in future space missions due to significant transmission delays and reduced bandwidth. They advocate for technologies that improve situational awareness (SA) for both astronauts and remote mission control. Their paper outlines a usability study on integrated timeline tools, which aim to predict and resolve potential mission constraints, ultimately supporting more successful and autonomous space missions.

Heinicke et al. [4] advocate for an even broader perspective that views inclusion not merely as a gesture of diversity but as a means to improve mission outcomes. They propose that space agencies should integrate individuals with various disabilities into the design and planning processes of space missions, thereby fostering innovation and resilience in space exploration.

While distinct in their approaches, these contributions underscore the importance of integrating autonomy, modular design, and innovative design methods to address the unique challenges of future space missions as we aim to reflect with our new UI for the CubeSat mission.

The design of UIs plays a crucial role in satellite mission operations, enhancing operator efficiency and minimising errors. Effective UI design requires the involvement of domain experts in the decision-making process [19]. NASA's Open Mission Control Technologies (OpenMCT)[4] is an open-source initiative aimed at providing customisable and extensible mission control UIs [3].

Dashboard design and data visualisation are critical for monitoring satellite operations effectively. Well-designed dashboards consolidate data from various sources, offering a comprehensive view of multiple mission statuses and improving decision-making and historical analysis [7]. The choice of visualisation techniques significantly influences the clarity and interpretability of complex data, ensuring that operators can extract meaningful insights [14]. Research highlights the importance of real-time data visualisation in operational contexts, aiding in the rapid analysis of evolving scenarios [17].

A crucial aspect of dashboard design is the integration of data from multiple sources to enhance situational awareness and historical analysis [7]. Selecting appropriate data visualisation methods ensures that complex information is presented in an accessible manner, allowing operators to identify critical insights swiftly [14]. User-centric design principles further enhance dashboard usability by prioritising intuitive layouts and ensuring the timely accessibility of relevant data [11]. Engaging stakeholders throughout the design process helps tailor dashboard features to specific operational requirements, leading to improved user adoption [20].

To maximise effectiveness, dashboards should incorporate key performance indicators (KPIs) relevant to mission operations, facilitating real-time monitoring and control [14]. The inclusion of feedback mechanisms allows continuous improvement based on user experiences

[4] `https://nasa.github.io/openmct/`

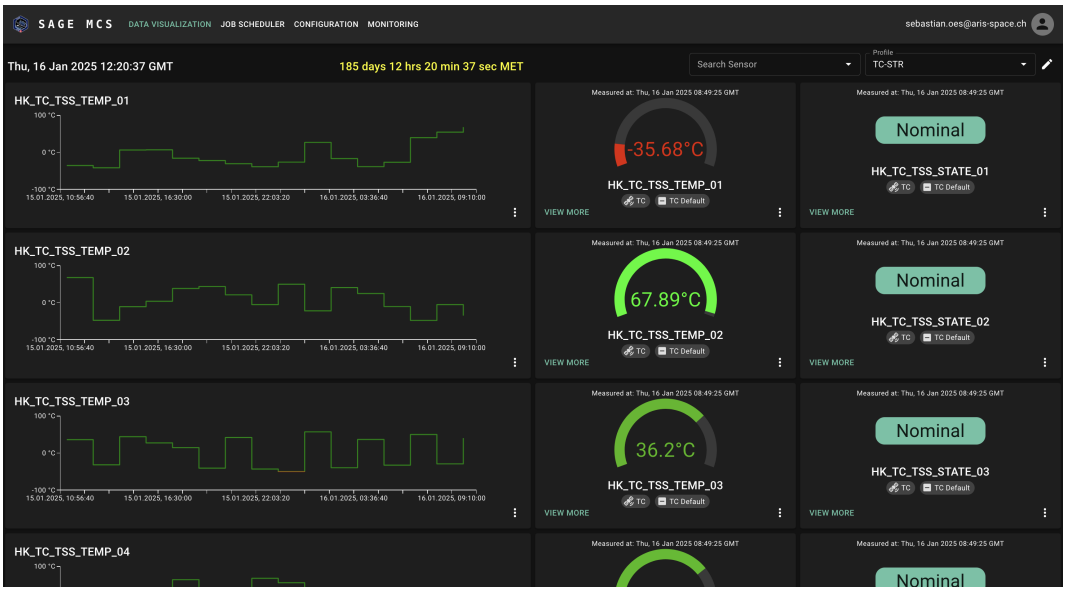

Figure 2 Example Dashboard for the multi-mission CubeSat control software for the SAGE mission.

and operational outcomes [8]. However, challenges such as data overload and the need for ongoing operator training must be considered to optimise dashboard utility and ensure long-term usability.

Despite advancements in multi-mission control software, CubeSat operations, and UI design, existing solutions often lack the simplicity and accessibility required for effective multi-mission CubeSat operations centres. Many systems do not provide integrated, user-friendly dashboards that balance flexibility, customisation, and intuitive design. Non-configurable mission control software that is tightly coupled to a specific mission or mission type leads to additional development overhead that does not align with the rapid development cycles of CubeSat missions. This research aims to address this gap by developing dashboards that are easy to implement and operate, guided by user-centred design principles and informed by operator feedback through user interviews.

3 User Interface Design

Therefore, designing an effective UI for mission control software requires balancing usability, cognitive load reduction, and adaptability to diverse operational roles. As stated in the previous section, related research highlights the importance of usability in such interfaces [12] to facilitate intuitive interaction. Building on the related work, the UI of the SAGE MCS was developed to ensure efficient data visualisation, seamless navigation, and adaptability to mission needs. This section outlines the UI architecture, key design principles, and findings from our iterative evaluation process.

3.1 Concept and Modular Design

The SAGE MCS UI is structured into three primary modules: theme, page structure, and views. This modular approach enables parallel development, ensuring that modifications to one component do not impact others. The initial design considerations focused on visual

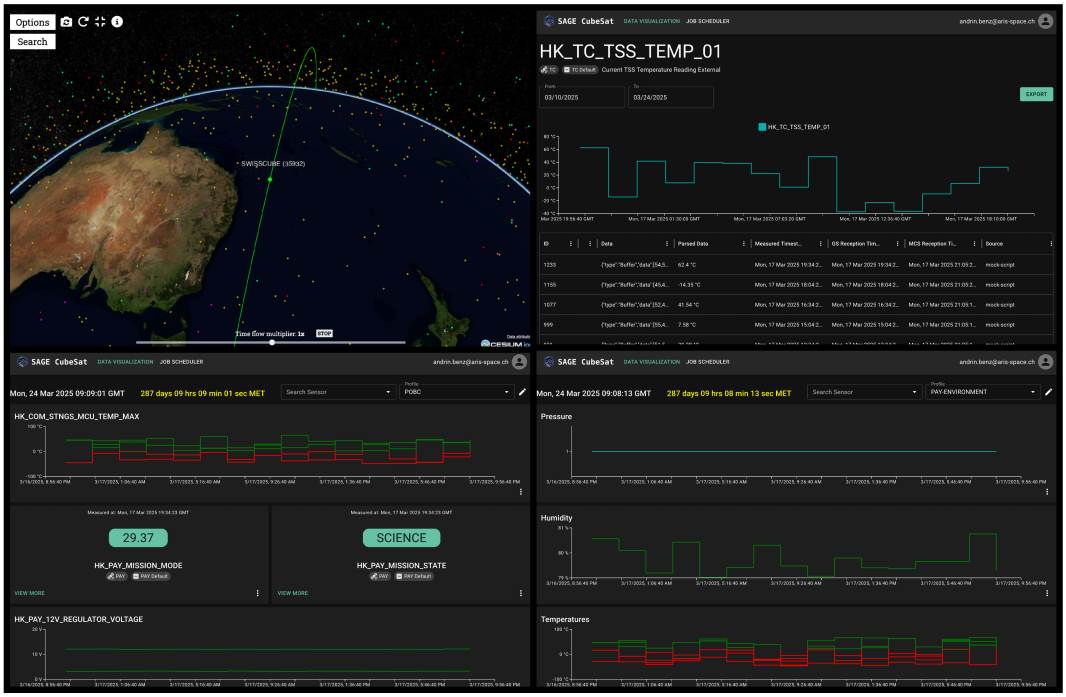

Figure 3 Alternative Dashboard Configurations for the multi-mission CubeSat control software for the SAGE mission.

clarity, consistency, and responsiveness to support operators in high-stress mission scenarios. Key principles included using visual cues to distinguish interactive elements, maintaining consistency in icons, colours, and layout to facilitate learning and reduce errors, and providing immediate feedback through hover effects and visual confirmations to enhance user confidence. Additionally, minimising cognitive load was a priority to enable users to concentrate on mission-critical tasks rather than interface navigation.

The SAGE MCS UI is structured around a modular dashboard layout that enables users to tailor their views based on specific operational roles. This approach ensures that mission-critical data is presented in a clear and accessible manner while allowing for flexibility in adapting to different user needs. Figure 2 shows an example of the dashboard used in the multi-mission CubeSat control software. Figure 3 shows alternative configurations of the dashboard.

The dashboard incorporates several key controls essential for mission operations. A Zulu Time display provides real-time system time for synchronisation across mission teams. Alongside this, a Mission Time counter tracks the elapsed duration of the mission, ensuring precise timing for operational procedures. To facilitate rapid access to telemetry data, the dashboard includes a Sensor Search function, enabling users to locate specific sensor readings efficiently. Additionally, the Profile Selection feature allows users to switch between predefined or customised dashboard profiles, ensuring that the displayed information aligns with their specific tasks and responsibilities.

The system supports configurable dashboards that can be dynamically adjusted to match operational requirements. Each dashboard is based on modular cards, which serve as the primary means of visualising mission data. Users can select from predefined profiles or create

custom configurations that reflect their individual workflows. This flexibility ensures that mission operators can focus on the most relevant information without being overwhelmed by extraneous data.

A diverse set of cards is available within the dashboard, each designed to support different types of data representation. Static cards provide essential reference materials, including textual descriptions, images, and quick-access links to external resources. Data cards offer a more interactive means of presenting mission telemetry, utilising charts, tables, maps, and real-time visualisations to display evolving sensor data. In addition, mission-specific cards cater to the unique requirements of space operations, featuring tools such as 3D satellite models, actuator state visualisations, system alerts, and sensor imagery. These elements collectively contribute to a comprehensive and adaptable interface supporting routine monitoring and critical decision-making.

To ensure consistency, usability, and accessibility across various devices, the UI adheres to Material Design principles [16]. This design framework provides a structured approach to visual hierarchy, interaction patterns, and responsive layouts, allowing for seamless operation across different screen sizes and platforms.

4 Evaluation

An iterative evaluation process was conducted to ensure that the design met operational requirements, involving key stakeholders throughout the development cycle. This approach ensured continuous feedback, enabling the refinement of system functionalities to better support mission operations.

4.1 Initial Stakeholder Discussions

The development process commenced with structured meetings involving representatives from the Mission Operations (MOPS), Payload (PAY), and On-Board Computer (OBC) teams. These discussions provided an initial overview of the system's objectives and constraints. Following a collaborative session, the fundamental architectural decisions were established: the software would be web-based, hosted externally, and structured around a REST API to ensure scalability and interoperability. This architecture was selected to support seamless data exchange between subsystems while maintaining a user-friendly interface for mission operators.

4.2 User Story Development

Each subteam was tasked with defining user stories to ensure that the system aligned with mission needs. These user stories captured the specific requirements of operators and engineers, detailing the interactions necessary to monitor and control mission parameters effectively. The user stories were compiled into a structured document, serving as a reference for feature prioritisation. The document queries users for specific information related to each interaction with the system. This provides the development team with a clear understanding of which system components are involved in a given interaction, which parameters are passed, and what return values and post-conditions are expected. On top of functional requirements, the user stories provided non-functional stakeholder requirements. One of the key insights that emerged from this process was the necessity for flexible, role-specific dashboard profiles. Given the distinct responsibilities of different operators, it became evident that a configurable interface was essential to prevent information overload and streamline workflows.

4.3 Iterative Development and Feedback

Following the initial requirement gathering, an iterative development cycle was established. Weekly review sessions were held with stakeholders, allowing for continuous refinement of the UI and dashboard configurations. These iterative improvements were informed by direct user feedback, ensuring that practical operational needs guided design choices.

Once the core dashboard functionality was implemented, a usability workshop was conducted with representatives from each subteam. Participants were provided with early interface prototypes and tasked with evaluating their effectiveness in supporting their workflows. They completed structured questionnaires, providing insights into usability, clarity, and feature relevance. The feedback gathered from this session directly influenced the refinement of dashboard layouts, interaction patterns, and data visualisation methods.

4.4 Expert Evaluation at GSOC

To validate the system in a real-world operational context, an expert evaluation was conducted at the German Space Operations Center (GSOC) of the German Aerospace Center (DLR). During this visit, the development team had the opportunity to observe mission control rooms used for the operation of satellites such as TerraSAR-X and TanDEM-X. These observations provided valuable insights into best practices for mission-critical interfaces, particularly in terms of information presentation, workflow integration, and system responsiveness.

A structured feedback session was held with domain experts in mission planning, communications, and operations engineering. This session confirmed several key design assumptions and highlighted critical aspects of interface usability. One of the primary findings was the importance of data abstraction: users should only be presented with information relevant to their specific tasks. For instance, a payload operator requires access to subsystem-specific data, while a communications engineer focuses on signal acquisition metrics. Presenting excessive or irrelevant data can lead to cognitive overload, reducing situational awareness and increasing the likelihood of errors.

The SAGE MCS dashboard's role-based configuration aligns with these principles, allowing users to customise their views according to their operational needs. By filtering information based on user roles, the system ensures that mission-critical data is presented in a clear and accessible manner, optimising decision-making and operational efficiency. The expert evaluation at GSOC validated this approach, reinforcing the importance of configurable dashboards in mission control environments.

5 Implementation & Operation

Prior to developing the SAGE MCS, a collaborative process involving all relevant stakeholders was done to formulate the technical requirements, ensuring alignment with mission objectives. Three core principles guided the infrastructure design: prioritising essential features for mission success, ease of installation and learning through automation, and resilience to ensure continuous operation. These principles shaped a robust and efficient infrastructure, optimised for functionality and durability.

5.1 Hosting and System Architecture

The SAGE MCS is hosted externally on cloud servers, selected based on key requirements such as high availability, log retrieval, rollback capabilities, manageable costs, and strong security measures. This ensures uninterrupted access, system integrity, and compliance with

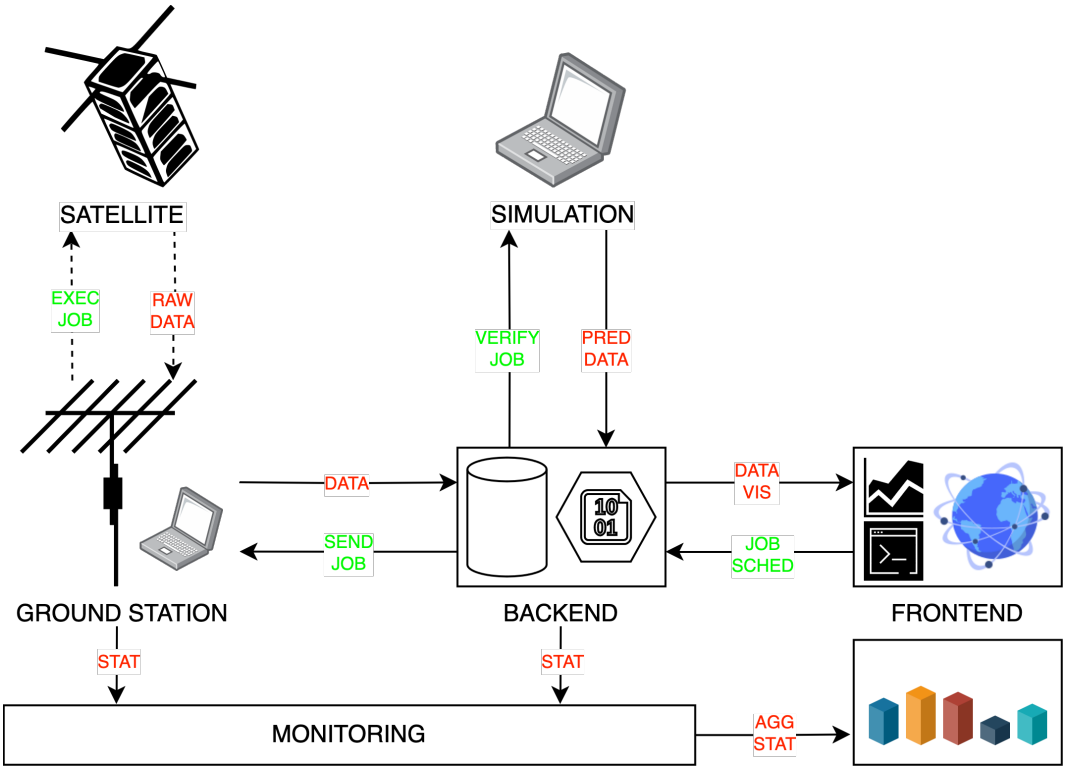

Figure 4 Overview on the setup.

industry standards, supporting the Mission Operations Centre. The MCS features a resilient core component that interfaces with external services through API calls, ensuring scalability and availability across CubeSat missions, as shown in Figure 4.

5.2 Backend, Frontend, and Simulation Integration

The backend, built with Node.js, TypeScript, and Express.js, follows the Router-Controller-Service (RCS) pattern to enhance scalability with robust error handling and logging. The Drizzle ORM ensures efficient data management. The UI, developed using React and Next.js, provides a responsive, modular interface with enhanced visualisation and interaction through React Material UI, Three.js, and Leaflet. The system also integrates with a simulation module for real-time satellite state modelling, ensuring command sequence verification in a risk-free environment. Additionally, the UI supports multiple ground stations for redundancy, automatically handling duplicate sensor data and ensuring broad mission compatibility.

5.3 Monitoring, Alerting, and Communication

The monitoring system, powered by Grafana and Prometheus, tracks performance and health metrics, generating alerts for any anomalies. Iris incident response software ensures quick resolution of issues by automatically notifying engineers via Slack. Communication between services is managed through secure RESTful APIs with error handling and logging to maintain system integrity.

5.4 Quality Assurance and Documentation

The system uses CI/CD pipelines, linting, and automated testing to ensure high-quality code, with unit and end-to-end tests validating system functionality. Mock data generation scripts can support stakeholder feedback by simulating satellite states and system behaviours. Comprehensive documentation, using Docusaurus, supports knowledge transfer and system maintenance, ensuring the sustainability of the mission control software across multiple team members that regularly change in student-led missions as well.

6 Conclusion

The SAGE MCS demonstrates a modular and flexible approach to multi-mission CubeSat control software. By prioritising simplicity, user-centric design, and comprehensive documentation, the system effectively addresses key challenges faced by student-led CubeSat missions, including high team turnover and constrained resources.

The iterative development process, guided by continuous stakeholder feedback, has resulted in a robust architecture and intuitive UI that aligns with the operational requirements of the SAGE CubeSat mission. This ensures reliable mission operations while enhancing operators' situational awareness and decision-making.

Future work could explore extending to support a broader range of missions and vehicles, including robotic systems for terrestrial and space applications. The architecture was designed with scalability in mind, facilitating such expansion.

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Multidimensional Usability Assessment in Spaceflight Analog Missions

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Abstract

Software planning tools enable the self-scheduling of operational timelines during spaceflight, reducing reliance on ground support crews. Here, we assess analog crew perceptions of a planning tool's usability across two space mission analogs with two validated questionnaires: the unidimensional System Usability Scale and the multidimensional User Experience Questionnaire. Critically, half the missions had assistive countermeasures integrated into the planning software interface whereas the other half did not. Correlation tests revealed high convergence between usability measures in the spaceflight analog setting. Group comparisons showed that the interface countermeasures enhanced several dimensions of usability, particularly for perceptions of the tool's efficiency and dependability. These findings highlight the utility of a multidimensional approach to characterizing usability in order to capture fine-grained shifts in human-software dynamics, especially in spaceflight environments.

2012 ACM Subject Classification Human-centered computing → HCI design and evaluation methods

Keywords and phrases space usability, crew autonomy, self-scheduling software

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1 Introduction

The National Aeronautics and Space Administration (NASA) has envisioned that future astronauts will operate autonomously, without relying on ground support, due to communication latencies as exploration missions venture deeper into space [15]. Thus, new technologies and standards must become a core part of space operations to enable crew autonomy and keep deep space crews resilient to varying degrees of isolation. Given the large number of novel technologies that crews will encounter, it is imperative that these technologies be highly usable; they must be efficient, effective, easy to use and learn, and generally associated with a positive user experience [2, 18].

Prior work demonstrates the feasibility of quantitative approaches to assessing the usability of tools in the aerospace and spaceflight domain (e.g., [7, 17]). Many factors contribute to product usability, but not all factors apply to all products equally. While there are many usability questionnaires available, none incorporate every possible metric [23]. Therefore, the choice of which questionnaire to use can be product- or domain-specific.

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NASA's recommended metric to validate usability is the System Usability Scale (SUS; [5]), a questionnaire that captures overall user perceptions in a single score. In user experience (UX) today, SUS is the most widely used usability questionnaire and is considered simple, reliable, and valid [19]. A proposed threshold for acceptable usability is a SUS score of 85 out of 100 [1]. Most recently, efforts have led to the development of a NASA-specific modified SUS (NMSUS; [4]) that has curated questions for space-relevant technologies.

While the SUS quantifies usability on a single encompassing dimension, usability has traditionally been considered a multidimensional concept. Nielsen [18] described five key attributes of usability: learnability, efficiency, memorability, errors, and satisfaction. Paralleling this, much empirical work has aimed to develop a multidimensional usability questionnaire that is brief and sensitive to variations in design. One example is the User Experience Questionnaire (UEQ; [12]), a 3–5 minute survey that breaks down usability into six subscales: attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty [20]. Shelat and colleagues [21] demonstrated the UEQ could capture fine-grained differences in the user experience of various planning interface designs. It remains unclear how different dimensions of the UEQ relate to the SUS in space environments, although it is reasonable to predict that they will be strongly positively correlated. This paper evaluates the relationship between SUS and UEQ multidimensions regarding assessing the usability of a spaceflight scheduling interface. Given the development of the NMSUS, verifying that the SUS and UEQ converge in spaceflight analog environments is a primary aim here.

Self-scheduling is one important capability required for space crews to become autonomous from Earth-based ground support. Research efforts at NASA have culminated in developing a self-scheduling software tool, Playbook, which allows astronauts to manage their own operational timelines [15]. Akin to a calendar, users can see their planned schedule as well as the schedule for the rest of the crew. Their schedules are laid out horizontally so that each crew member's timeline can be seen concurrently. Users can add new activities or add activities from a predetermined list. More frequently, assigned crew activities can be rescheduled or reassigned by simply dragging and dropping them along or between timelines. These activities have modeled constraints (e.g., the exercise activity uses the treadmill) and Playbook automatically checks if the rescheduled activity fulfills all its constraints (e.g., two people are not trying to use the same treadmill simultaneously).

As part of this ongoing research, Playbook is used to evaluate self-scheduling performance [14]. Controlled lab experiments were used to determine performance based on schedule characteristics (e.g., type of activity constraints). In an analog environment, we focused on assessing overall acceptability and usability, with and without visual aids to support self-scheduling performance. These visual aids, identified as countermeasures, were designed to facilitate scheduling and rescheduling, providing "No-Go" zones and suggested violation resolution [24, 10] (Figure 1). The primary countermeasure visualizes where an activity can be scheduled that meets the activity's constraints; any constraint violations are indicated with warning markers for the user to fix. If activity is scheduled on a "No-Go" zone, the user should expect the activity to create a violation.

The Human Exploration Research Analog (HERA) is an isolated spacecraft analog at the NASA Johnson Space Center used to simulate space exploration missions. This analog provides a unique opportunity to analyze spacecraft technologies in an isolated and confined environment over a relatively long mission (i.e., 45 days) with an "astronaut-like" crew. The usability data in this paper was collected over two campaigns, HERA Campaign 6 (C6) and Campaign 7 (C7). In the present work, we had two primary aims: 1) to demonstrate convergence between the SUS and the UEQ using data from astronaut-like participants in

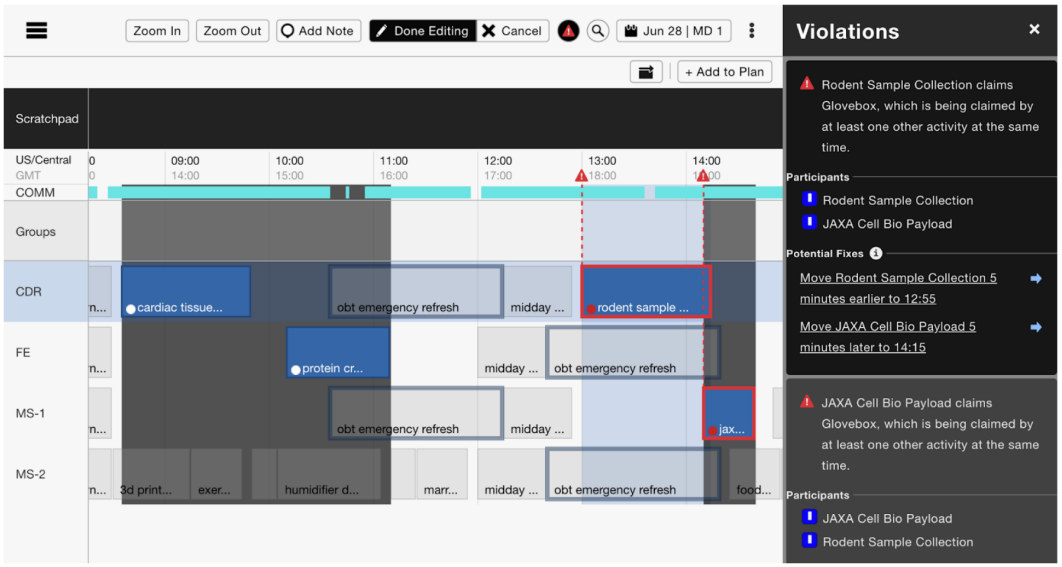

Figure 1 Visual countermeasure aids: "No-Go" zones (dark grey) and suggested violations solutions.

two HERA campaigns and 2) to test whether these conventional survey instruments can be leveraged to detect differences in usability based on software interface countermeasures in a spaceflight analog. With this, our broader goal was to show that conventional survey-based usability testing can be integrated into spaceflight analog environments to validate the deployment of tools designed for astronautic operations.

2 Methods

2.1 Materials

We administered two validated usability questionnaires post-mission: the System Usability Scale (SUS; [5]) and the User Experience Questionnaire (UEQ; [12]). The SUS is a unidimensional 10-item questionnaire that prompts participants to indicate how much they agree with several statements regarding a tool or product on a 5-point Likert scale. One example item is "I found the various functions in this system were well integrated." A score is calculated by first coding responses to odd-numbered items from 0 to 4 and even-numbered items from 4 to 0. After, responses are summed and multiplied by 2.5 such that a minimum score is 0 and a maximum score is 100.

The UEQ is a 26-item survey that breaks usability into six discrete dimensions. Each item is an adjective that participants rate on a 7-point Likert scale (-3 to +3) as they pertain to the user experience of a tool or product. Here, we define the six UEQ subscales with an accompanying example item:

- Attractiveness: Do users like or dislike the tool? (enjoyable)
- Perspicuity: Do users find it easy to learn how to use the tool? (understandable)
- Efficiency: Can users solve their tasks without unnecessary effort? (practical)
- Dependability: Does the user feel in control of the interaction? (supportive)
- Stimulation: Do users find the tool exciting and motivating to use? (interesting)
- Novelty: Do users find the tool design creative and leading edge? (inventive)

We calculated scores on each of these dimensions using a data analysis tool (v12) provided by developers of the UEQ (`https://www.ueq-online.org/`). Attractiveness is generally considered an overall user experience metric, whereas perspicuity, efficiency, and dependability are more pragmatic qualities. Similarly, stimulation and novelty are considered hedonic qualities. The multidimensional structure of the UEQ enables researchers to isolate precise shifts in usability, which has proven useful for evaluating spaceflight tools (e.g., [21]).

2.2 Procedure

We analyzed data from 32 astronaut-like crew members who participated in an isolated 45-day simulated space mission to Phobos. This simulated spaceflight mission occurred over two HERA campaigns. Each campaign consisted of four missions, and each mission was assigned a crew of four participants. During the mission, participants faced varying communication latencies and were instructed to follow operational timelines using Playbook; they could also schedule and reschedule part of their own operational timelines on Playbook. In Campaign 6, each participant was required to entirely self-schedule one operational day to be executed by the entire crew. Campaign 6's Missions 1 and 2 did not have Playbook countermeasures, whereas 3 and 4 did [16]. In Campaign 7, each participant completed this self-scheduling task twice, resulting in 8 self-scheduled mission days. We counterbalanced countermeasure exposure in Campaign 7, where Missions 1 and 2 did have countermeasures, whereas 3 and 4 did not. Participants could also use Playbook to spontaneously self-schedule flexible tasks on their timelines [3]. At the end of each mission, participants completed the SUS and UEQ surveys regarding their experience with Playbook. This study was approved by the NASA Institutional Review Board under expedited review (STUDY00000187) and determined to be no greater than minimal risk.

3 Results

First, we assessed the degree of coupling between SUS scores and different dimensions of the UEQ. We merged UEQ and SUS data ($n = 32$) from Campaigns 6 and 7 before performing Pearson correlation tests. The results are presented in Figure 2. All dimensions of the UEQ were significantly positively correlated with SUS, although it is worth noting that the dependability dimension was most tightly interlinked with SUS scores.

Next, we aimed to test whether either the SUS or the UEQ are sensitive enough to detect Playbook usability differences in spaceflight analogs based on the presence of scheduling interface countermeasures. We first split our sample into two groups: those with countermeasures ($n = 16$) and those without ($n = 16$). Next, we performed Welch's independent samples t-tests, assuming unequal variances in each UEQ dimension and overall SUS score. Due to the small sample size in each group and concerns about non-normality, we augmented this analysis with a permutation-based approach (e.g., [6]). We shuffled the "with" vs. "without" countermeasures group labels and recalculated the t-statistic 10,000 times for each test. This process creates a null distribution of t-statistics that does not rely on any parametric assumption. A p-value can then be extracted by taking the proportion of permuted t-statistics that exceed the original observed t-statistic. We present these permuted p-values along with other statistical information in Table 1. The group comparison is visualized in Figure 3.

For research conducted in high-fidelity spaceflight simulations such as HERA, statistical power is constrained by low sample size due to selective participant criteria. Because of this, we focus on effect sizes (Cohen's d of 0.2 as small, 0.5 as medium, and 0.8 as large; [8]) in addition to significance thresholds for each t-test ($\alpha = 0.05$). The results

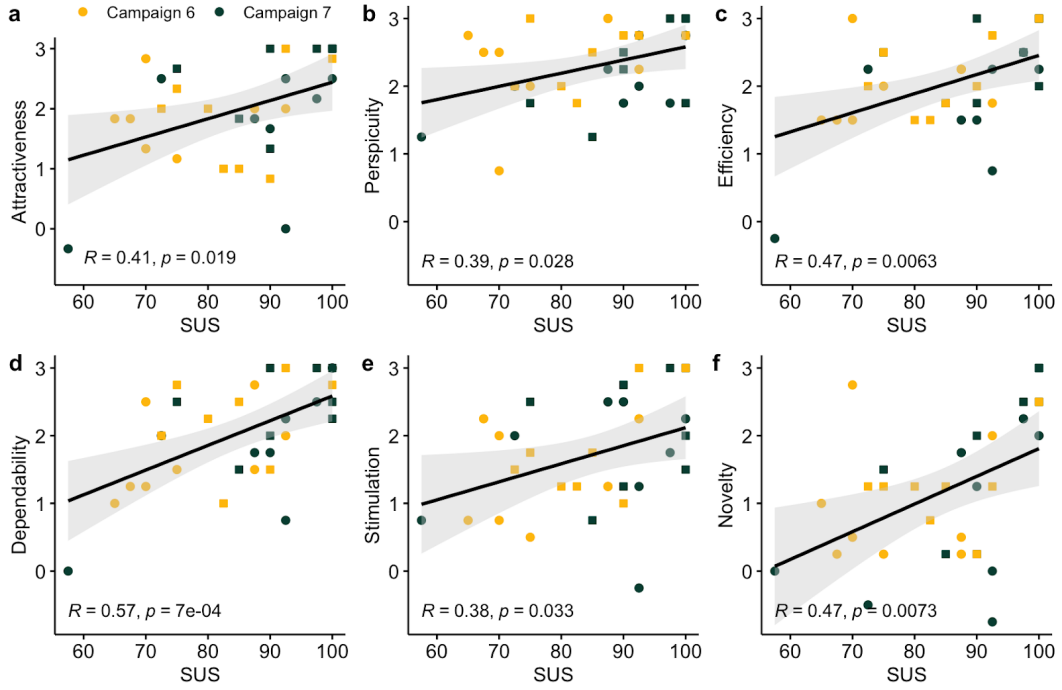

Figure 2 Pearson correlations between overall scores on the SUS and the a) Attractiveness, b) Perspicuity, c) Efficiency, d) Dependability, e) Stimulation, and f) Novelty dimensions of the UEQ. Gray shading represents the 95% confidence interval. Gold and dark green points represent HERA Campaigns 6 and 7 data, respectively. Squares and dots represent participants with and without countermeasures, respectively.

showed that countermeasures conferred small to large benefits to usability on all dimensions. Countermeasures moderately enhanced attractiveness ($p = 0.092$, $d = 0.61$), efficiency ($p = 0.033$*, $d = 0.75$), stimulation ($p = 0.106$, $d = 0.58$), novelty ($p = 0.059$, $d = 0.71$), and SUS ($p = 0.090$, $d = 0.60$), although only the effect on efficiency was statistically significant. There was a small positive but nonsignificant effect on perspicuity ($p = 0.405$, $d = 0.29$) and a large, significant effect on dependability ($p = 0.018$*, $d = 0.86$). The results suggest that countermeasures improve Playbook's usability in spaceflight analogs. This effect is particularly pronounced for the usability dimensions of efficiency and dependability.

4 Discussion

Developing new, usable technologies for space crew autonomy is essential as long-duration exploration missions venture deeper into the unknown. Here, we analyzed crew perceptions of a self-scheduling software tool, Playbook, which is designed to enable crew autonomy. Over two 45-day campaigns in simulated spaceflight, astronaut-like crew members used Playbook to build operational timelines. Post-mission, they filled out a battery of questionnaires to characterize Playbook's usability on several dimensions. We found that scores on the SUS (a single-dimensional survey on overall usability) and on different facets of the UEQ (a six-subscale survey) were highly correlated. We also showed that countermeasures integrated into Playbook's user interface enhanced usability on multiple dimensions, with effect sizes ranging from small to large. These countermeasures elicited the strongest significant

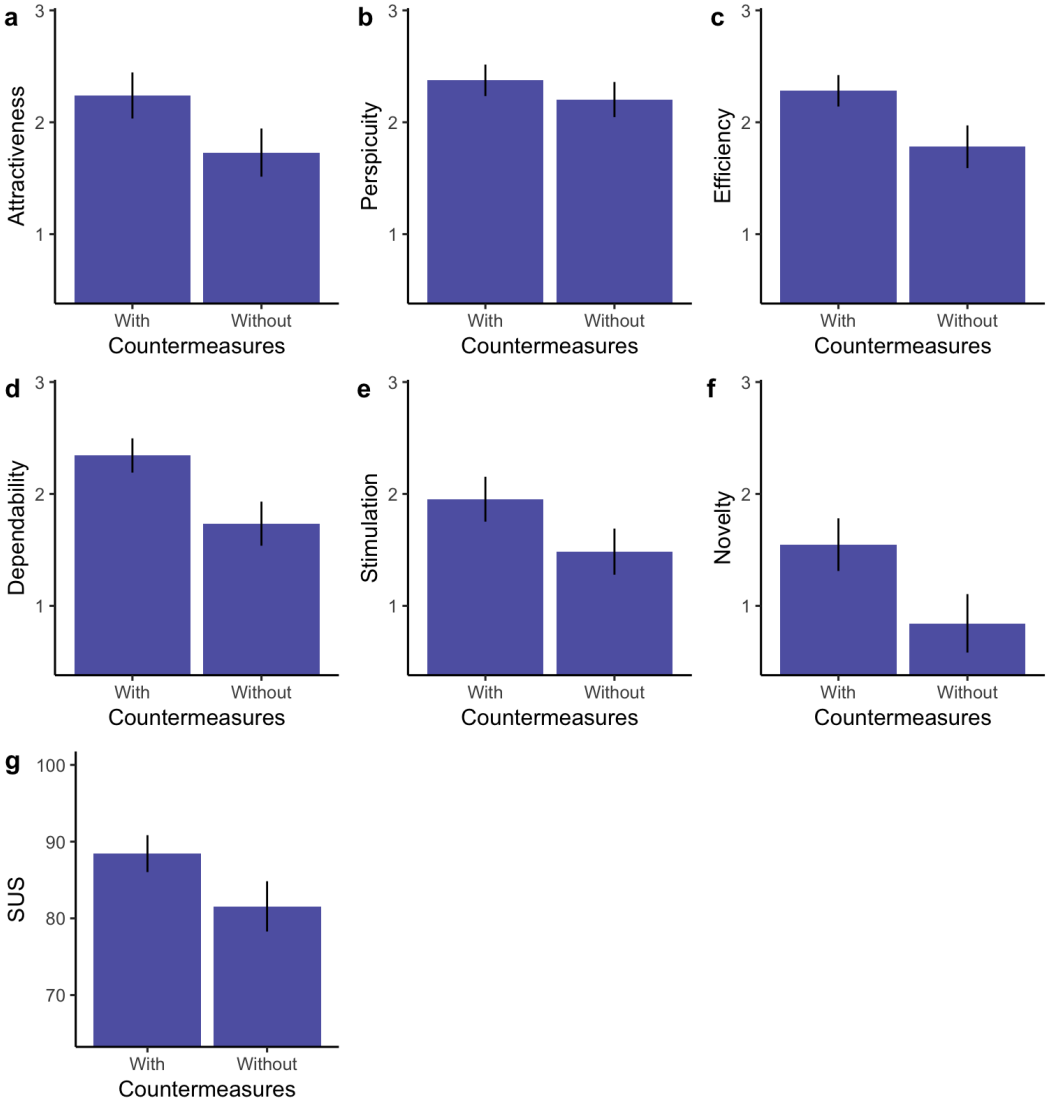

Figure 3 Group comparisons between HERA crew members with vs. without countermeasures on a) Attractiveness, b) Perspicuity, c) Efficiency, d) Dependability, e) Stimulation, f) Novelty, and g) SUS total. Error bars represent standard error.

Table 1 Welch's independent samples t-tests on usability dimensions between HERA crewmembers with vs. without Playbook interface countermeasures.

	Mean (standard deviation)					
Variable	**With**	**Without**	**t**	**df**	**p**	**d**
Attractiveness	2.24 (0.82)	1.73 (0.86)	1.71	29.94	0.092	0.61
Perspicuity	2.38 (0.56)	2.20 (0.63)	0.82	29.65	0.405	0.29
Efficiency	2.28 (0.56)	1.78 (0.76)	2.11	27.57	0.033*	0.75
Dependability	2.34 (0.61)	1.73 (0.79)	2.44	28.26	0.018*	0.86
Stimulation	1.95 (0.80)	1.48 (0.82)	1.63	29.98	0.106	0.58
Novelty	1.55 (0.94)	0.84 (1.04)	2.00	29.68	0.059	0.71
SUS	88.44 (9.61)	81.56 (13.10)	1.69	27.52	0.090	0.60

increase in perceived dependability and efficiency. Altogether, these results demonstrate convergence between a conventional usability survey recommended by NASA [1] and a newer, multidimensional survey only recently deployed in spaceflight contexts [21].

The findings speak to the utility of breaking down usability into discrete, quantifiable subdimensions to capture narrower shifts in usability due to interface changes. UEQ+, a modular tool that allows researchers to add more factors to the base UEQ, could further improve the flexibility of the questionnaire and its effectiveness in space environments. For example, UEQ+ has been validated to evaluate Trust and Voice User Interfaces, two examples likely relevant to future spaceflight UI [9, 11]. Having established that SUS is correlated with UEQ, future work with the new customizable UEQ+ has the potential to show even more precise conclusions.

The results affirm Playbook as a usable tool for spaceflight operations. Prior work has put forward score ranges to determine the rough acceptability of a tool based on overall SUS scores [13]: A+ (84.1 - 100), A (80.8 - 84.0), A- (78.9 - 80.7), B+ (77.2 - 78.8), B (74.1 - 77.1), B- (72.6 - 74.0), C+ (71.1 - 72.5), C (65.0 - 71.0), C- (62.7 - 64.9), D (51.7 - 62.6), and F (0 - 51.6). It is worth noting that without countermeasures (M = 81.56, SD = 13.10), Playbook receives an A; with countermeasures (M = 88.44, SD = 9.61), this is pushed to an A+. Similarly, NASA's *Human Integration Design Handbook* [1] states that usable systems usually get a SUS score of 85. Again, Playbook exceeds this threshold with countermeasures, but not without. A multipronged consideration of user attitudes (as we have done here), objective scheduling performance metrics [14, 10], and even conversational indices of collaborative scheduling [22] is necessary to paint the full picture of human-software dynamics for crew autonomy.

Furthermore, our objective results are consistent with our subjective user feedback. After each mission, crews are asked to name three things they liked about Playbook. Crews commented on the user interface's attractiveness and ease of use, and many appreciated the ability to conduct self-scheduling during the HERA missions. For example, one crew member mentioned how they liked "Freedom to make my schedule. One user who had the "No-Go" zone countermeasure mentioned "Ability to see restrictions/issues" among their top three Playbook qualities.

Our conclusions are not without limitations. First, without a direct comparison between Earth and real space conditions, it is possible that certain aspects of extreme environments that are not present in HERA (e.g., microgravity) shape usability. This remains an open research question in studying human spaceflight operations. Second, usability needs and priorities are likely different during space missions when compared to terrestrial operations.

However, NASA currently requires terrestrial usability evaluations, which is why SUS and UEQ were selected as measures [1]. Since the SUS and UEQ were originally developed for Earth tools, this raises the possibility that some usability dimensions may be more important than others in space contexts. Mission context, complexity, and duration may have effects on usability. For the SUS, some have started evaluating these differences [4], but not yet for the UEQ. Space HCI would benefit from the consideration of these gaps moving forward.

We have shown here that such a multidimensional usability approach can be used to fully characterize usability in simulated spaceflight missions. If users are given time to fill out a 5-minute survey, the data enables researchers to identify where a tool may be lacking and then improve that area. This sets the stage for the deployment of tools such as Playbook to enable crew autonomy during actual operations. A valuable future step would be to assess longitudinal usability assessments to see how these perceptions evolve; this approach is especially feasible for participants in controlled, long-duration analog environments.

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Designing for Usability in Modular Space Habitats: A Space Syntax Perspective

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Abstract

As human ambitions turn toward establishing settlements on the Moon and Mars, the architectural and spatial configuration of these habitats has received comparatively little attention relative to their engineering systems. This paper explores the spatial configuration and architectural usability of modular extraterrestrial settlements, focusing on their potential growth, vulnerability, and navigability. Drawing from architectural theory and Space Syntax methods, we propose a novel framework for evaluating habitat layouts based on two key metrics: intelligibility and vulnerability. Using a combination of analytic tools and simulations – including adapted versions of the "beady-ring" growth model – we assess both small-scale configurations and larger aggregated settlements. We introduce a new vulnerability metric based on spatial types and configurational redundancy, allowing us to quantify how module failure can fragment a habitat system. Our findings confirm five core hypotheses, including the inverse relationship between structural resilience and spatial intelligibility as modular settlements scale, and the applicability of Space Syntax theories to non-terrestrial environments. We argue that without deliberate planning, accretive modular growth leads to declining usability, and we advocate for intentional and informed planning interventions, to sustain human-centered design at larger scales. This work provides a foundational methodology for evaluating and guiding the spatial evolution of off-world settlements.

2012 ACM Subject Classification Human-centered computing → Interactive systems and tools; Human-centered computing → Interaction design process and methods

Keywords and phrases Space Syntax, architectural usability, intelligibility, lunar habitats, Mars habitats, modular design, human-centered computer simulation

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1 Introduction

There is a growing interest in the prospect of human settlements on the Moon and Mars. Evidence for this surge in attention can be found across multiple domains: in media coverage of high-profile proposals, such as Elon Musk's vision of a million-person colony on Mars [12]; in a steady increase in academic publications; in Google Trends data since 2004; and in the proliferation of policy documents, conferences, and design competitions [7] addressing


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extra-terrestrial habitation. This growing discourse is mirrored by an expansion of scientific research into the technical challenges such settlements might face. For instance, a recent systematic review [10] considered over seventy studies focused on lunar and Martian regolith simulants for plant growth, underscoring the significant interest in sustaining life off-world. However, while technical issues such as agriculture, radiation shielding, and thermal control dominate much of the literature, fewer studies explore the spatial configuration of these habitats – and the usability and vulnerability implications of their growth over time. Both these concepts will be defined in the next section.

When it comes to imagining how a lunar or Martian habitat might be designed and function, most visions converge around a common approach: modularity. As early as 1989, NASA reports described habitat subsystems as including *"life support and thermal control systems, pressure vessels and internal structure, communications and information management systems, and interior outfitting,"* and emphasized that *"the constructible habitat has egress hatch ports for connection . . . "* [3]. Subsequent designs have largely followed this logic, favoring a modular "stick-and-ball" approach (to borrow a phrase from chemistry), in which domed or cylindrical habitation units are connected incrementally. Some proposals are single-storied, others multi-level; some are subsurface, fully or partially regolith-covered; but the principle of accretive modularity remains a frequently shared constant.

In the early stages, a base is likely to begin with a single habitat with additional modules delivered on subsequent missions. Over time, and with increased functionality, such a base may reach or exceed the scale of the International Space Station, or current Antarctic research settlements. While in-situ construction methods are anticipated, most projections assume standardized interfaces and metrics across modules. What this implies is a spatial configuration that evolves incrementally – often unpredictably – with modules added as needed rather than through comprehensive master-planning.

Coming from a combined background in architecture and human-computer interaction, the authors of this paper argue that current visions of modular habitat-systems are predominantly shaped by engineering-driven definitions of utility and function. While these designs address essential environmental and mechanical needs, they often overlook the spatial, perceptual, and experiential dimensions that are fundamental to architecture. We propose a layered model of habitat usability and functionality in which higher-order qualities – such as legibility, comfort, spatial resilience, and navigability – are dependent on the successful resolution of more basic technical challenges (Figure 1). This framework underscores the need to treat spatial configuration not as an afterthought, but as a critical component of successful design.

We suggest that after meeting basic engineering and survival functions (shelter, safety, and so forth), the next most critical task is to solve – or at least balance – the spatial configurational functions (Layer II of the pyramid). It is this second layer that is most directly impacted by the challenge of evolving, sprawling, accretive growth. Our paper seeks to address the often-overlooked importance of this configurative level of modular settlement design, and to apply established methods for examining urban spatial complexity to the outcomes of their development over time.

Many of the largest proposed habitat designs remain relatively "simple" in spatial terms, in that they function – and are often conceived – as singular buildings rather than as true settlements [9][28]. We argue that a structured method for scaling complexity from individual habitats to larger, interconnected settlements – while maintaining acceptable architectural usability – is currently lacking. In response, we propose a novel habitat vulnerability measure, based on simple spatial types and their configurational redundancy, that quantifies the usability impact of a single module loss. Vulnerability is here defined both as a local risk – the configurational consequence of losing an individual module – and as a global metric of systemic resilience.

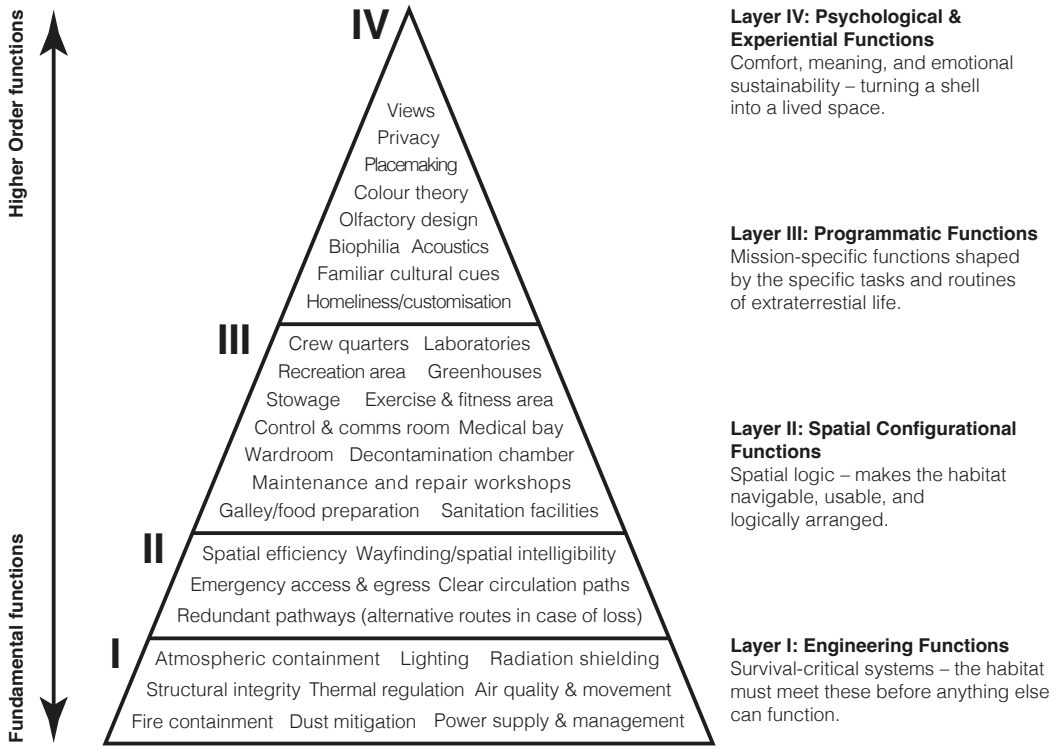

Figure 1 A functional hierarchy of extraterrestrial habitat architecture (after Hillier's theory of generic building function [14]). Note this is an indicative rather than exhaustive list of functions.

This work is guided by the following hypotheses, which are dependent on two key concepts, which we use extensively in this paper: *intelligibility* and *usability* which we will first define, before presenting the hypotheses. Intelligibility objectively measures how maze-like or confusing a layout is likely to be [14] and has been predictive of people becoming lost in complex environments. This leads to our definition of *habitat usability*, which we adopt from Krukar et al. [21] in which they present a formal model for understanding usability and user experience in an architectural context. They define a usable building one which is *"understood, learned [or learnable] and liked by their users, so they are able to do what they want, or need, to do effectively, efficiently and with satisfaction"*. We suggest that modular habitats must adhere to these principles to be considered *usable* and that *"learn[ability]"* is simply intelligibility.

- **H1** As simple, modular habitats aggregate beyond a certain size, intelligibility and usability will decrease without intentional and informed planning.
- **H2** Aggregations of modular habitats will have inherent vulnerabilities that can be captured through a combination of spatial and graph-theoretic analyses, providing a new measure of habitat vulnerability.
- **H3** As habitat-settlements increase in size, habitat vulnerability will naturally tend to decrease.
- **H4** Space Syntax theories and analytic methods, established in architecture, urban and built environment disciplines, can be applied to investigate both habitat vulnerability and habitat usability.
- **H5** For habitats to be effectively scaled up, from building-scale to small settlement-scale to city-scale, a strong theoretic basis for planning growth is required. [17]

Our paper is unique in applying Space Syntax methods and theories, currently used in architecture and urban planning (Section 2.2), to extraterrestrial settlements. In so doing, we demonstrate how modular habitats, as they aggregate and evolve into larger settlements, must be understood not only as technical systems but also as spatial configurational ones, and that their design must address both technical and spatial requirements.

2 Background and literature review

In this section, we will briefly introduce different types of habitat designs, establish how large a settlement is likely to grow, and also introduce the relevant Space Syntax concepts that can be applied to the analysis of such aggregations of habitats or settlements.

2.1 Modularity and existing habitat designs

As mentioned above, NASA's descriptions of habitat subsystems are focused primarily (and understandably) on the functional [3][5][4]. The consensus seems to be that early settlements will most likely consist of modular habitats linked together, via pressurized passages or tunnels, to form larger aggregations [13]. The modules being linked can be sorted into three sub-categories; hard-shell modules; inflatable or expandable habitats (essentially pressurized structures with their internal volume increasing after deployment); and lastly, structures made of in-situ resources (ISRU). These are termed classes-I, II and III respectively [19]. Prototype examples of class-I include the Habot module (habitat + robot), a pressured rigid vessel (with the ability to move) and a basic module diameter of 3.75m [6]. The Habot comes in multiple different types, with varying pressure port angles, which is of significance when considering layout possibilities.

Prototype examples of class-II include the "planetary surface habitat and airlock unit", a 3.65m diameter inflatable fabric structure [13] and the MB10 habitat [28], a three-storey inflatable structure which should reach a diameter of 26m when fully deployed. In another paper [28], Sinn presents a hypothesized aggregation of 19 such units in a densely packed honeycomb arrangement. Finally, the NASA TransHab project describes a hybrid type module combining a rigid core and inflatable exterior. It provides a four-storey, 3.35m wide inflatable habitat [18]. For spherical modules, Vogler [29] suggests that 4.0m diameter should be the minimum size. It appears that most deployable units are initially conceived of as being between 3m-4m in diameter. Class-III examples can be built using a number of construction methods applied to the ISRU, including 3D printing and brick-making [20][31][30].

All of the above examples permit a reconfigurable aggregation of modules. We have based our simulations on the Habot module, as it seems the best documented in terms of the range of different module-types and as it offers a variety of connector-layouts. Our next challenge was to consider how large an extraterrestrial city might reasonably be. Outside of the rich world of science fiction, we have struggled to find any considered discussion of how expansive an aggregation of modules might ultimately become. Pabila [26] suggests that they may expand to fill entire craters on Mars: *"The natural shape of the impact crater creates predetermined sized cities, or states that would spread to fill the crater."* Beyond the latter, some clue might be found in a presentation by Elon Musk in 2017 when he presented an artists' visualization of what a Martian city might look like [25] (Figure 2).

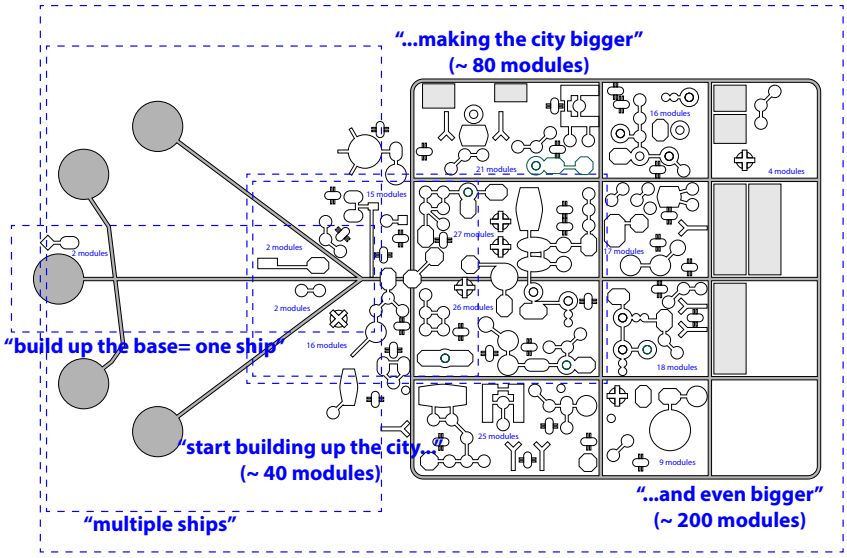

Figure 2 Visualization of Musk's impression of the growth stages of a Martian city, taken from his presentation at the International Astronautical Conference (IAC) 2017 at Adelaide [25]. The superimposed text are annotated quotes from his talk, showing that his vision of a "bigger city" seems to approximate 200 separate modules/habitats.

Setting aside the physical dimensions of the modules in Musk's presentation for the time being, a simple count of the number of modules at each stage of growth provides us with some insights. The settlement's initial phase expands from "one ship" to 40 modules. Expansion stage two doubles the size to 80 modules, whilst the latter "city-state" is depicted as reaching 200 modules. Notably, not all modules are shown as being physically connected, although it is reasonable to assume the presence of subterranean tunnels, or established external pathways between proximal airlocks. Given the lack of any other data, we have decided to simulate habitat aggregations for up to 200 modules. Such an approach captures the early-stage architectural level challenges of settlement growth and configuration, and as such helps to identify key architectural constraints and risks that any such habitat is likely to face in its more vulnerable formative years.

2.2 Relevant Space Syntax concepts

To better understand the growth of such extraterrestrial settlements, we can turn to architectural and urban theories such as Space Syntax. Space Syntax is a framework of architectural theories, spatial representations, analytic methods and software tools, primarily developed at University College London from the 1970s onward by Bill Hillier and colleagues. It seeks to understand the relationships between spatial configurations found in the built environment and people's use of, movement through and social interactions within them [15]. Space Syntax tools and methods are widely applied across different scales from simple to complex buildings, neighborhoods and small settlements, through to large cities and geographic regions.

Fundamentally, Space Syntax methods decompose any built environment into different types of spatial representations or "primitives," typically either convex spaces (spaces containing only mutually visible location pairs [15]), axial lines (longest lines of sight/movement, [27]), or isovists (visibility fields [1][23][24]). These spatial units are then typically represented as graphs, with spaces becoming nodes and edges representing spatial relations such as

adjacency, accessibility, and/or visibility. This approach allows the extraction of graph-based metrics, many of which have been shown to correlate with observed use or behavior, such as occupancy rates, pedestrian flow [16], getting lost [8], and architectural function. Whilst a comprehensive review of Space Syntax is beyond the scope of our paper, we use a selection of Space Syntax concepts: Hillier's space types; isovist field analyses and intelligibility; and "beady-ring" settlements. Below we briefly explain each in turn, and discuss how they are relevant to the modeling and analysis of aggregations of space habitats.

2.2.1 Hillier's space types

In this paper, we introduce (and extend) Hillier's concepts of *a*-, *b*-, *c*-, and *d*-space types [14]. He developed these classifications to distinguish connected spaces within a spatial system based on their contributions to connectivity, function, and movement. An a-space is a space with a single link or a dead end. *b*-spaces contain more than one link and are part of tree-like sub-systems. A *c*-space has more than one link and lies on a single ring or loop of circulation. Finally, a *d*-space must have more than two links and forms part of at least two overlapping rings. Importantly for our work, Hillier's definitions (Table 1) are derived from a graph-based theorizing of how the removal of each type affects the overall spatial network. In short, these classifications reflect the potential of each space to fragment a system's configuration.

Table 1 Definitions of space-link types, their roles, and the impact of their removal.

Type	Definition	Role in System	Impact of Removal
a-space	A space with a single link – a dead end.	Terminal point with no through-movement.	No effect on connectivity; system size reduced.
b-space	More than one link, part of a tree-like sub-system.	Local connector providing access to dead ends.	Removal fragments system; severity depends on node degree.
c-space	More than one link, part of a single ring.	Local integrator increasing local intelligibility.	Ring collapses into tree; no full fragmentation.
d-space	More than two links, part of overlapping rings.	Global connector maintaining system-wide integration.	High impact; may reduce redundancy and increase depth.

Although not explicitly conceived with settlement vulnerability in mind, Hillier's framework implicitly begins to capture it; yet it lacks the necessary precision for assessing functional vulnerability in complex, modular systems such as space habitats. In the course of our work, it became clear that the removal of certain *b*-, *c*-, and *d*-spaces had a greater impact on the resultant/remaining spatial network than others. Not all spaces of a given type are equal; and so, a distinguishing sub-categorization of Hillier's original definitions became necessary.

We term these special-case subsets b^*-, c^*-, and d^*-spaces, and collectively refer to them as *star-hub spaces*. In each case, the * distinction reflects the addition of a branch connector that does not alter the base classification of the space, but significantly increases the degree of system fragmentation that would result from its removal. These sub-classifications are defined as follows:

- A b^*-space is a *critical tree connector* – a key branching point in a tree configuration, whose removal causes the system to fragment into more than two parts.
- A c^*-space is a *critical ring connector*.
- A d^*-space is a *critical multi-ring connector*, where the space links multiple rings or ring-tree interfaces, meaning that their removal would result in widespread disconnection or potential system failure.

Finally, as we began testing habitat layouts, we identified an entirely new spatial category. This type is similar in form to a *b*-space, in that it has more than one link and exists within a tree configuration – but rather than accessing a dead end, it serves to connect two or more ring configurations. In doing so, it acts as an essential bridge within the overall configuration. We therefore classify it as an *e*-space (or *essential space*) and its more critical variant as an e^*-space. This particular spatial type appears especially relevant to the challenges of complex extra-terrestrial settlement design and system vulnerability. In summary, it is clear that Hillier's taxonomy of space types has potential to become highly useful for extraterrestrial settlement design analysis, despite not having been conceived with such an application in mind.

2.2.2 Isovist fields, integration, and intelligibility

An isovist represents the geometric bounds of space directly visible from a single location, providing a simple unit of spatial experience [1]. From that unit a number of geometric and relational metrics can be extracted [2]. If isovists are calculated throughout a spatial system (typically but not exclusively represented in plan form), their visual links and overlaps can be used to form dense sets of data. Such fields (commonly visualized as colored spectra) describe both locally experiential qualities and broader spatial relations in the system. Whilst numerous Space Syntax measures can be developed in the above way, two have particular value for our study. The first, *integration* ([15][23]), is a relativized "centrality" measure that reveals the visual depth structure of a spatial network. While integration values are identified on a per-node basis the second numeric measure is the system wide one of *intelligibility*. This is the correlation between integration and spatial connectivity (how many other spaces – in this case an isovist – intersects or overlaps; in the special case of isovists this is also equivalent to isovist area).

2.2.3 "Beady-ring" settlements

Hillier and Hanson identified the form of "beady rings" [15] when analyzing small vernacular settlements which seemed organized around an irregular ring street and resembling beads on string. They observed that it had arisen by an accumulative process of small-scale decisions which was amenable to simulation. The subsequent beady-ring algorithm simulates these small settlements through an aggregation process of sequentially placing a dyad-pair of "building+connecting space" such that all new spaces *must* adjoin an existing space. Simulations of this process produced settlements resembling the settlements they had studied. In this paper we utilize a modified version of the beady-ring simulation to simulate the growth of extraterrestrial habitat settlements.

3 Methodology

3.1 Replication of "Habot" configurations

We began by redrawing 25 module configurations from Cohen [6], using his layouts as a basis for a broader analysis of modular systems (Figure 3). These include a variety of connection types and pressurized port arrangements. We analyzed each layout for the distribution of Hillier's space types (*a*-, *b*-, *c*-, *d*-), our new critical space types (b^*, c^*, d^*, *e*, e^*), and the number of circulation rings. We also used the *Isovists app* [24][23][22] to calculate the *integration* and *intelligibility* values, establishing a baseline for spatial usability. A new vulnerability measure was also calculated.

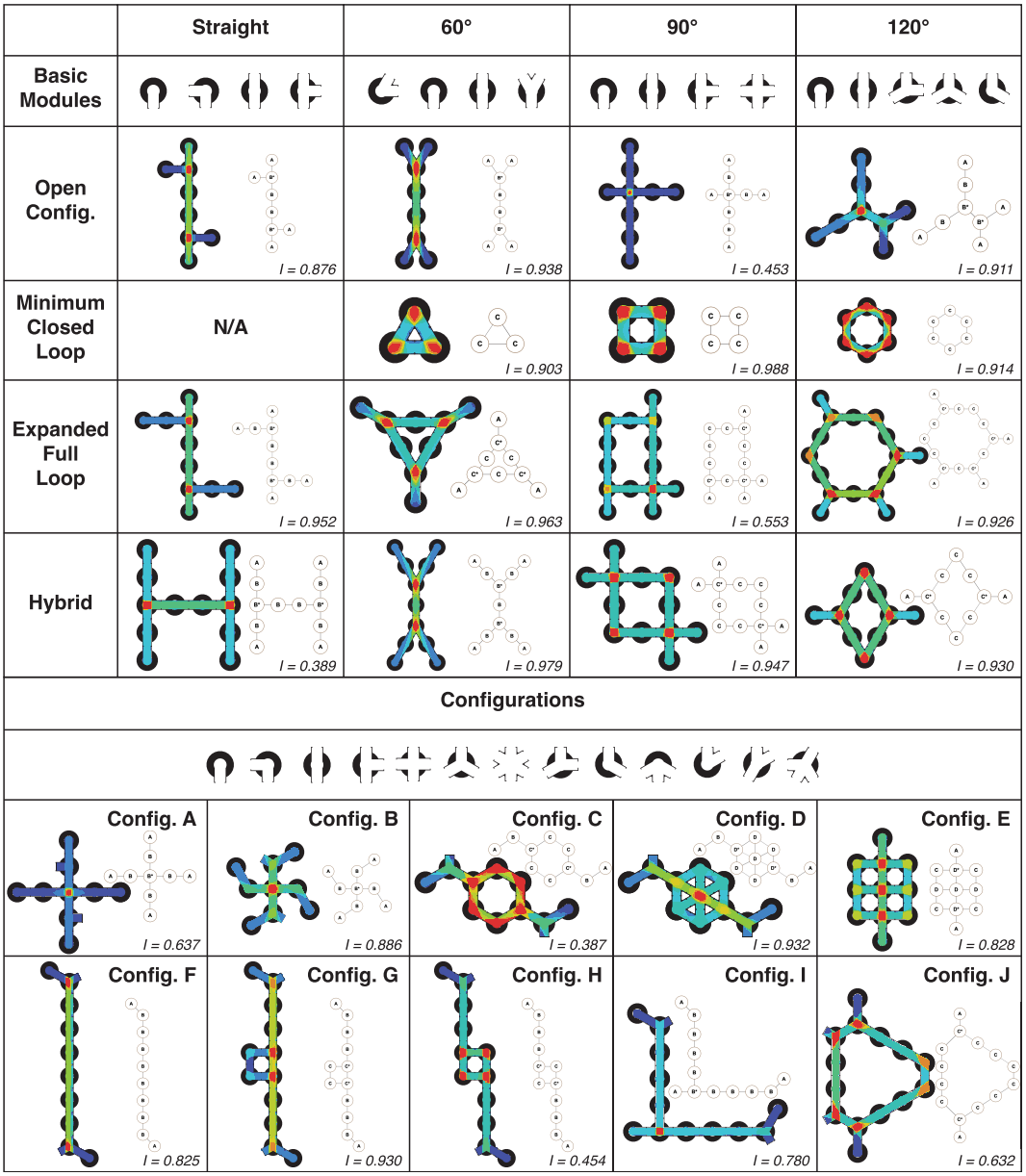

Figure 3 25 Habot configurations, based on Cohen's figures 10 (top) and 12 (bottom) [6] and colored according to isovist field measure of *integration* (red = highly integrated; blue = segregated). The space-types are also indicated in a space-type diagram along with the *intelligibility* score (*I=0.XXX*) value for each configuration. The higher the intelligibility value the less confusing and maze-like the layout – min = 0 and max = 1. (N.b. the classifications of "straight" versus "90°" were used in the original paper [6] and we decided to retain these terms for ease of comparison even if the distinction between them is somewhat unclear.)

3.2 Simulating habitat larger habitat settlements and complexity

To test our theory, we simulated four large settlements of 75, 100, 150, and 200 modules using an adapted version of Hillier and Hanson's "beady ring" algorithm, based on habitat-connector compatibility rules. In each case, modules were placed, by the software, in a

semi-random order but constrained to connect only to available ports on previously placed habitats, reflecting the opportunistic but rule-governed nature of accretive growth. These were exported as vector-based plans (.dxf) and analyzed in the *Isovists app* [24][23][22] to calculate integration and intelligibility, as well as the distribution of Hillier's original plus new critical space types (*a*-, *b*-, *c*-, *d*-, *e*, b^*, c^*, d^* and e^*). We then generated an additional 25 large settlements, each containing 100 habitats, in GraphML format, unsuitable for isovist-based field analysis, but ideal for calculating the distribution of space types and vulnerability scores (Section 3.3).

3.3 Measuring "vulnerability"

The vulnerability measure analysis was applied to all 29 city-scale configurations (as well as to the original 25 small settlements). Next, we developed a new metric for habitat vulnerability to quantify and compare the inherent resilience of settlement configurations. We define vulnerability at two levels: *local vulnerability*, which assesses the impact of the loss of access to each individual module (due to pressure loss, maintenance, contamination, repair, and so forth); and *global (or systemic) vulnerability*, an evaluation of the overall resilience of the whole system. Each metric can be considered in absolute terms, although we suggest normalizing global vulnerability by the total number of modules in the system.

To calculate the true vulnerability of a settlement configuration, we begin by identifying all habitats whose removal would split the settlement into two or more disconnected parts. These include every *b*-space, b^*-space, c^*-space, d^*-space, and any extended categories such as *e*- and e^*-spaces. *a*-spaces (single-connection dead ends) are excluded, as their isolation is trivial and expected; the same applies to ordinary *c*- and *d*-spaces which are considered only when they act as structural connectors (their starred variants).

We then subject *every* habitat – critical or otherwise – to a uniform random-failure test. For each habitat, (h), containing (N) modules we temporarily remove it from the settlement and record the size of the largest surviving, disconnected section and then normalize by the remaining settlement size $(N-1)$ or (L) [11]. The space-type categories decide whether $(L(h)=1)$ (for non-splitting *a*-, *c*-, *d*-spaces) or $(L(h)<1)$ (for *b*-, b^*-, c^*-, d^*-, *e*-, e^*-spaces), so their structural role is fully embedded in the calculation. Averaging those scores over all (N) habitats yields the expected post-failure connectivity. In the two analytically tractable extremes – a perfect ring and an infinitely long line – the expected vulnerability is 0 and 0.25, respectively. Multiplying this by 4 therefore stretches the range to [0,1] and anchors the scale at "perfectly robust" (ring) and "maximally fragile" (path). The final vulnerability score is:

$$V = 4 - \frac{4}{N} \sum \frac{(\text{size of the largest disconnected section})}{N-1} \tag{1}$$

High global vulnerability values indicate that significant portions of a habitat-system are vulnerable to fragmentation and configurational collapse if key nodes are removed or blocked. In this way, the measure directly reflects a settlement's configurational fragility. Conversely, low values would indicate a degree of configurational resilience. Similarly, high local vulnerability values identify critical modules within the whole system, and vice versa.

4 Results

4.1 Small settlements (Habot configurations)

Figure 3 shows the results of analyzing Cohen's 25 Habot configurations [6] and the location of *a*-, *b*-, *c*-, *d*-, *e*-, and the "star hub" space-type modules. Navigable space has been colored according to *integration* – a necessary computational stage towards calculating intelligibility. High-integration spaces are shown in red, with the spectrum shifting through green to blue for lower-integration spaces. We also present the resultant *intelligibility* values for each configuration (the higher the value, the less confusing and less maze-like the layout).

Figure 4 shows the number and proportion of *a*-, *b*-, *c*-, and *d*-space types in the original Habot configurations (Section 2.2.1) It is clear that a high proportion of some space types contributes to an inherent vulnerability of the layout. We also calculated the number of rings (also known as cycles in graph theory), and counted the number of independent rings, nested rings, and total rings in each layout. A ring in a layout contributes to the redundancy of that layout: if a module forming part of a ring becomes unusable (due to damage, contamination, repair, blow-out, depressurization, etc.), the rest of the modules can still be reached without passing through the non-functioning module. This continuity of space is important for the circulation of people and life support.

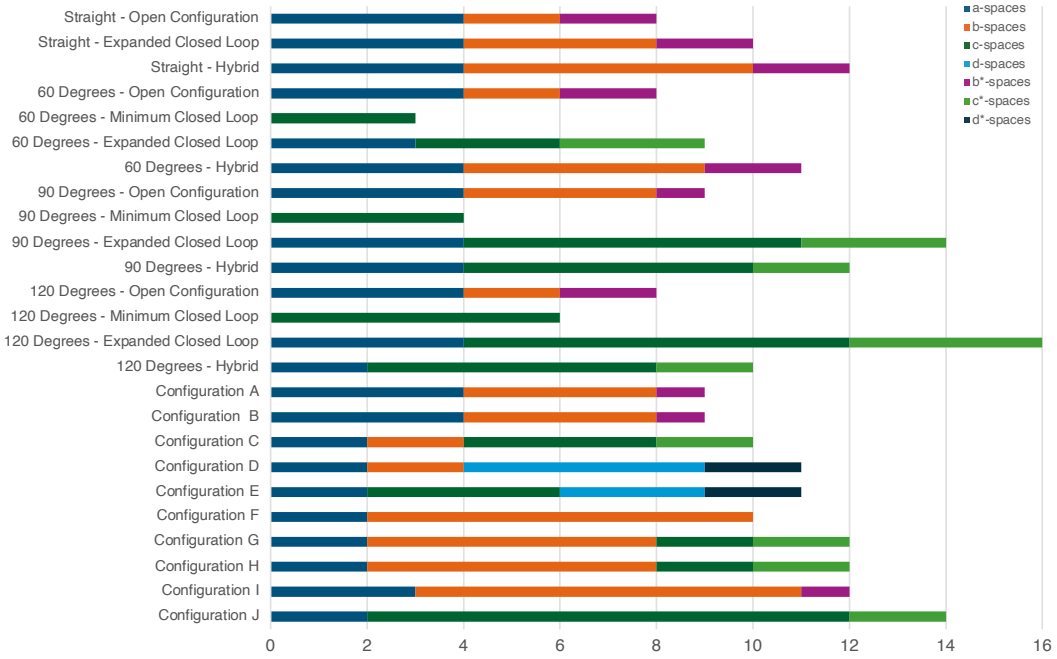

Figure 4 Number and proportion of constituent space types in the 25 Cohen configurations.

For independent rings, 56% of Cohen's layouts contained at least one ring, with the number of rings ranging from 1 to 6. Only 2 layouts contained nested rings, with the highest number being 15 total nested rings. Finally, we calculated the resultant *vulnerability* score for each small configuration, as shown in Table 2.

Table 2 Vulnerability scores (0 = the least and 1 = the most vulnerable layouts) for 25 small habitat configurations.

Name of configuration	Vulnerable Habitats	Total Habitats	Vulnerability Score
Straight – Open Configuration	10	8	0.71
Straight – Expanded Closed Loop	16	10	0.71
Straight – Hybrid	14	12	0.46
60 Degrees – Open Configuration	10	8	0.71
60 Degrees – Minimum Closed Loop	0	3	0.00
60 Degrees – Expanded Full Loop	3	9	0.17
60 Degrees – Hybrid	9	11	0.36
90 Degrees – Open Configuration	10	9	0.56
90 Degrees – Minimum Closed Loop	0	4	0.00
90 Degrees – Expanded Full Loop	6	14	0.09
90 Degrees – Hybrid	4	12	0.12
120 Degrees – Open Configuration	8	8	0.57
120 Degrees – Minimum Closed Loop	0	6	0.00
120 Degrees – Expanded Full Loop	4	16	0.07
120 Degrees – Hybrid	2	10	0.09
Configuration A	10	9	0.56
Configuration B	10	9	0.56
Configuration C	6	10	0.20
Configuration D	6	11	0.22
Configuration E	2	11	0.15
Configuration F	20	10	0.89
Configuration G	8	12	0.61
Configuration H	8	12	0.61
Configuration I	26	12	0.79
Configuration J	2	14	0.04

4.2 Habitat city simulations

Examples of the results of the "beady-ring" habitat growth simulation, and distribution of space types, can be seen in Figure 5. The distribution of the space types in the simulated cities differs from those in the smaller configurations (Figure 4). For the larger settlements, *b*-spaces, b^*-spaces, c^*-spaces, and d^*-spaces were the least commonly occurring space types, while *a*-spaces and *c*-spaces were significantly more prevalent, reflecting the accretive nature of large-scale growth. To test this further, we generated an additional 25 simulated city layouts (in GraphML format only) each consisting of N=100 habitats. We determined the number of different space types for each layout. For these additional, simulated settlements, the most frequently occurring space types were *c*-spaces (spaces on a single ring) and *a*-spaces (the ends of linear sequences). These formed, on average, 22% and 21% of all habitats, respectively. In the middle of the distribution were the *d*-spaces (spaces on multiple rings) and *b*-spaces (two-connector spaces as part of tree-like subsystems), each of which constituted 16% of the spaces. The least frequently occurring spaces were the *star-hub types* – c^*-spaces, b^*-spaces, d^*-spaces, and e^*-spaces – the configurationally critical space in the event of failure. They represented 12%, 8%, and 5% of all large-scale habitats, respectively. The new *e*-spaces and e^*-spaces typically constituted $< 1\%$ of habitats.

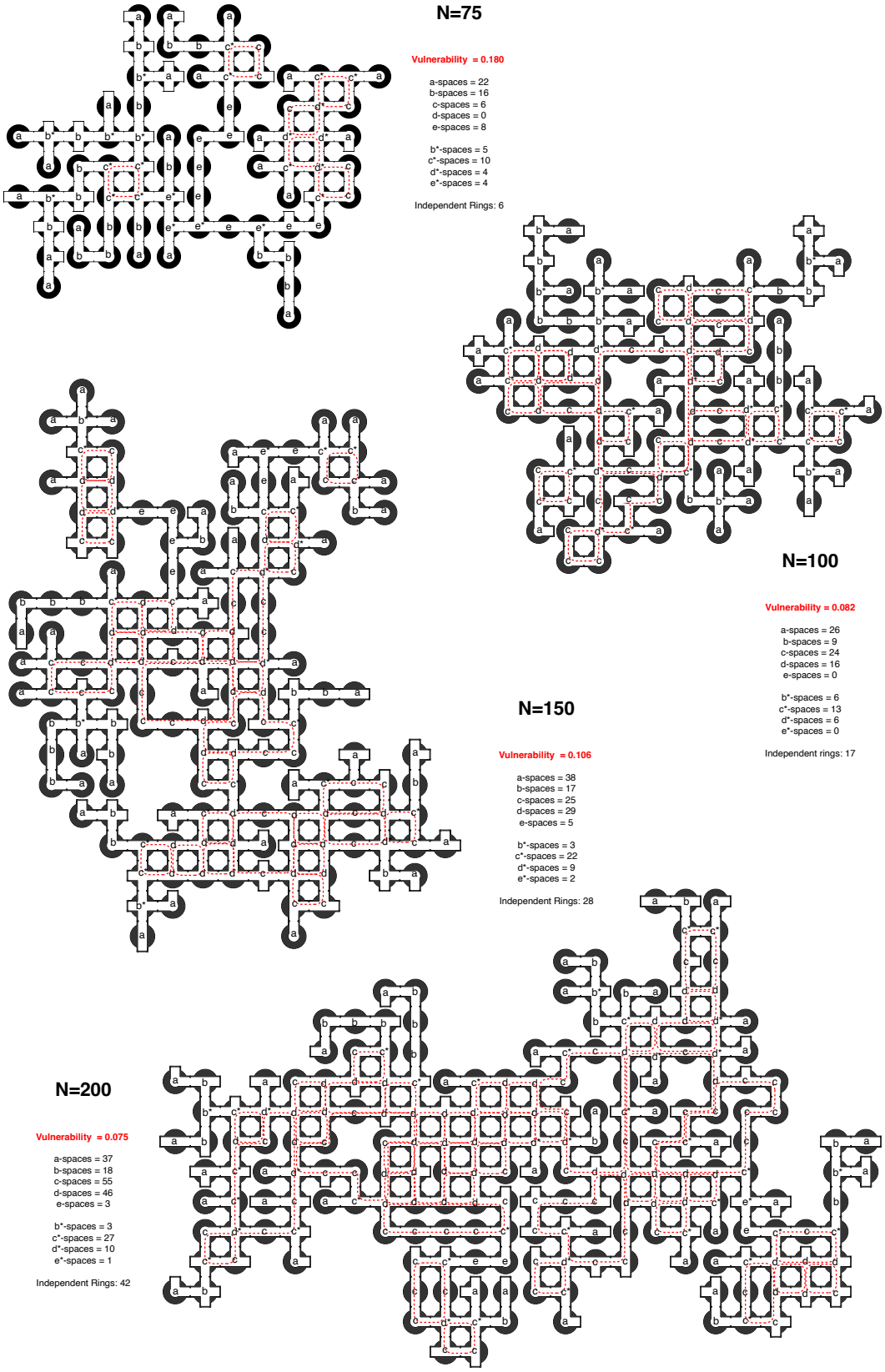

Figure 5 Four habitat settlements (N=75, N=100, N=150 and N-200 habitats) generated using a modified "beady-ring" algorithm. Space-types are shown superimposed on the habitats and circulation rings are indicated by red dotted lines. (N.b. the values in this figure are true *only* for these specific example layouts and are not intended to be representative of all settlements of the same size.)

The *intelligibility* scores of the settlements (a measure of how confusing or maze-like a settlement is) are markedly lower than those of the 25 Cohen small layouts. For $N = 75$, intelligibility is $I = 0.336$; for $N = 100$, $I = 0.686$; for $N = 150$, $I = 0.302$; and for $N = 200$, $I = 0.467$. These four simulated "beady-ring" layouts have an average intelligibility of $I = 0.448$. Compare this value to the 25 Cohen layouts, which have a mean intelligibility of $I = 0.797$, which can be interpreted as "highly intelligible" and also notably higher than the intelligibility of the larger settlements (Figure 5). (As a general heuristic, $I < 0.500$ may be interpreted as indicating a maze-like and confusing configuration.)

The *vulnerability* scores of the four simulated cities are: for N=75 vulnerability is 0.180; for N=100 vulnerability is 0.082; for N=150 vulnerability is 0.106; for N=200 vulnerability is 0.075. On average, the 25 Cohen layouts have a mean vulnerability score of 0.291 which is interpreted as being moderate (excluding the perfect rings, which by definition have a V of 0.000, the mean vulnerability is 0.419 (more vulnerable) and a standard deviation of 0.291. For the four large, simulated beady-ring layouts (Figure 5), the mean vulnerability score is 0.111. The average vulnerability score across all 25 additional GraphML habitats (N = 100) is 0.342 and also less vulnerable than the 25 Cohen layouts. If we plot all 54 vulnerability scores (25 Cohen layouts + 25 GraphML simulations + 4 large settlements (Figure 5)) against their settlement size (i.e. total number of habitats) simple linear fit gives a coefficient of determination: $R^2 = 0.294$). Thus, only about 29% of the variance in vulnerability is explained by the size of the settlement alone; the remaining 71% depends on the mix of habitat/space types rather than on the total habitat count.

5 Discussion

Validating the beady-ring simulation approach

The adapted "beady-ring" algorithm proved successful in generating large-scale modular settlement configurations with realistic accretive characteristics. By applying modified habitat-connector compatibility rules, the simulation was able to replicate the organic growth dynamics typical of extraterrestrial modular habitats and allow meaningful spatial analysis. These simulations provided a valuable testbed for evaluating spatial properties – particularly *integration*, *intelligibility* and *vulnerability* – at a scale beyond anything previously modeled.

Stabilization of space-type distributions and vulnerability scores

One important and potentially surprising outcome of our analysis is the stabilization of Hillier's space-type distributions as settlement size increases. While the smaller 25 Cohen configurations showed high variability in the proportions of *a*-, *b*-, *c*-, and *d*-spaces – along with their more critical b^*-, c^*-, d^*-, *e*-, and e^*-types – the larger simulated settlements (comprising four fully analyzed layouts and 25 additional graph-based simulations) demonstrated remarkably consistent proportions. This suggests that as modular settlements grow, they begin to exhibit predictable and self-organizing spatial typologies. From a design perspective, this is significant: if spatial properties tend to stabilize through accretive growth, it may be possible to anticipate and guide future configurations more effectively.

As space-type distributions stabilize, so too do associated vulnerability measures. Because vulnerability is defined by the impact of losing structurally critical nodes (specifically b^*-, c^*-, d^*-, *e*-, and e^*-spaces), their normalized value (as a proportion of total modules) tends to decrease as the number of modules increases. This supports the hypothesis that larger

settlements are inherently more resilient to localized failures – a trend confirmed across our dataset. However, this apparent configurational robustness comes with a trade-off, which is usability.

Decreasing intelligibility with growth

Intelligibility – defined as the correlation between local visibility (isovist connectivity/area) and global configurational depth (isovist integration) – tends to decline as modular habitats increase in scale. This trend, observed for the 25 Cohen configurations and the four simulated cities, highlights a key usability challenge: as spatial systems grow, they become harder to understand and navigate. This is consistent with Hillier's theories of urban complexity, which suggest that unstructured spatial growth leads to increased fragmentation and cognitive disorientation. In this context, while large settlements may be robust, they are also more functionally opaque – potentially making them difficult or stressful for inhabitants to use.

Preliminary findings suggest a relationship between intelligibility and vulnerability, although our dataset is not yet large enough for definitive statistical analysis. Nevertheless, the correlation is conceptually persuasive: as intelligibility declines, spatial legibility is lost, but at the same time, the systemic redundancy that supports resilience increases (larger configurations are *broadly* less vulnerable but the correlation coefficient is $R^2 = 0.294$). Therefore, if growth proceeds without spatial structuring, the risk of disorientation rises yet the risk of disconnection, and sub-system isolation, drops. This points to an important direction for future research – specifically, the possibility of defining spatial usability thresholds based on combined intelligibility–vulnerability scores.

Reassessing modular efficiency

Cohen [6] argued that a straight-run configuration of interconnected modules would be among the most efficient for early off-world habitats. While this may hold from a construction or logistical standpoint, our findings challenge this view from a spatial resilience perspective. In our analysis, straight-run configurations consistently ranked among the most fragile. Their linear configuration offers minimal redundancy and is highly susceptible to complete fragmentation if a single module is lost. From the standpoint of usability and resilience, such configurations appear among the least favorable for long-term habitation.

6 Conclusion

In this study we confirmed a set of hypotheses advancing our understanding of the spatial configuration and structural integrity of modular habitats. First, we showed that as modular habitats grow larger, their intelligibility – defined as the ease with which a system can be understood and navigated – inevitably decreases unless there is a structured and deliberate approach to their spatial organization. This supports our first hypothesis (**H1**), demonstrating that modular growth alone cannot sustain usability without strategic planning.

Second, our analysis confirms that aggregations of modular habitats possess inherent vulnerabilities that can be effectively captured through a combination of spatial and graph-theoretic analyses. By introducing a new measure of habitat vulnerability, we demonstrated that the structural fragility of modular habitats can be quantified and linked to specific spatial configurations. This finding confirms our second hypothesis (**H2**) and provides a novel analytical tool for evaluating habitat resilience.

We observed a critical trade-off as modular settlements increase in size: while the overall measure of habitat vulnerability tends to decrease with increased complexity and cyclicity or ringiness (indicating greater resilience), this comes at the expense of intelligibility and usability, which tend to decline proportionally. This directly supports our third hypothesis (**H3**) and highlights tensions between structural resilience and cognitive simplicity in complex spatial systems. However, the correlation between settlement size and vulnerability is weaker than anticipated ($R^2 = 0.294$)) and future work is required to further investigate this.

Moreover, our results confirm that methods derived from Space Syntax – which have traditionally been applied to urban and architectural analysis – are equally effective when extended to the analysis of modular habitats in extraterrestrial environments. This supports our fourth hypothesis (**H4**), showing that established Space Syntax analytic tools can be successfully adapted to new architectural contexts beyond terrestrial settlements.

Finally, we have shown that scaling habitat models from building-scale to settlement-scale and eventually to city-scale requires a strong theoretical framework. This validates our fifth hypothesis (**H5**), reinforcing the idea that spatial organization is necessary to sustain human navigation, learnability and usability within increasingly complex modular habitats.

Together, these findings establish a solid theoretical and analytical foundation for understanding the growth, organization, and vulnerability of modular habitats. They underscore the importance of balancing intelligibility and configurational resilience in the design of future extraterrestrial settlements and suggest that Space Syntax offers a powerful framework for guiding this process.

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VibroLink: A Wireless Vibro-Auditory Transmission System to Improve Situational Awareness During EVA

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Abstract

On earth, technicians rely on auditory or haptic cues, such as engine sounds and vibration, for a tacit understanding of complex machinery and its status. However, such vibrational cues are absent in space, potentially leaving astronauts unaware of safety-critical information about environmental changes during extravehicular activities (EVAs). This work-in-progress paper presents vibroLink, a concept for a standalone system designed to enhance situational awareness in spacewalks by wirelessly transmitting audio and vibration cues from machinery to the astronaut. Our approach employs a modular, two-component system: a transmitter (sensing) unit equipped with a piezo sensor that detects vibrations from machinery or other critical sources and a receiver unit with a vibrotactile actuator that can be attached, for example, to the astronaut's helmet to replicate the detected vibrations. A preliminary evaluation with a proof-of-concept prototype shows that our concept successfully transmits basic tactile cues, and naive users can leverage their tacit understanding of actions and materiality to identify how the cues originated.

2012 ACM Subject Classification Human-centered computing → Haptic devices

Keywords and phrases haptics, extravehicular activity, situational awareness

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1 Introduction

Extravehicular Activities (EVAs) are among the most challenging tasks astronauts undertake during space missions [1]. They expose astronauts to a harsh environment characterized for a lack of oxygen, atmospheric pressure, intense radiation, and microgravity. The bulky spacesuits required for astronauts to withstand such conditions limit mobility and sensory feedback [15], depriving astronauts of sensorimotor cues that could enhance efficiency and task performance.

On earth, when operating complex machinery, sound is always a present cue. For example, when driving a car, subtle changes in its sound alert us to its condition. Through audible and tactual vibration, we develop an implicit, *tacit* understanding of the car's operative state. This contrasts with *explicit* information communicated by designed indicators like warning lights or dashboard symbols. Similarly, technicians develop tacit knowledge regarding the status of machines; for example, automotive technicians can find the defective part of a car by hearing or feeling its vibration; this tacit knowledge, apart from the explicit knowledge, is crucial when repairing such complex systems [10, 17].

However, in outer space, these vibrations cannot propagate, due to the lack of a physical medium. For example, if an astronaut is fixing equipment during a space walk, they might miss 1) the vibratory response of the machinery that may indicate malfunctions or abnormalities and 2) safety-critical environmental information (e.g., two objects colliding or similar) because they cannot be sensed.


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In this work-in-progress paper, we propose a system to enable astronauts to access sensorimotor cues in outer space scenarios. The system consists of transmitter (sensing) and receiver units. The transmitter uses a piezo sensor to gather information about the vibration of a machine or surface and wirelessly sends this data to the receiver. The receiver has a vibroactuator that plays back the vibration. Both devices are designed to have a multi-use adhesive base, allowing astronauts to place the transmitters on critical machinery or surfaces and the receivers on, for example, their helmets. This provides astronauts with additional information about their surroundings without interfering with the design and function of other systems.

The vibroLink system is designed for ad-hoc use. It operates independently and does not require integration with existing technologies, allowing astronauts to deploy it as needed. Unlike conventional notification systems that require dedicated sensors, hardware, and planned integration, vibroLink can be deployed spontaneously – for instance, when an astronaut senses that something may be wrong. It then provides both useful status feedback and reassurance.

This paper is structured as follows. Initially, we explore existing research on the challenges of EVAs, sensory cues, tactile knowledge, and the application of haptic feedback in space environments. Subsequently, we introduce the proposed scenario for the vibroLink system. This is followed by a detailed description of the system's implementation and its evaluation. Lastly, we address the limitations of the system and outline directions for future research.

2 Related Work

This work builds on research done on sensory cues for complex tasks and tacit knowledge, as well as challenges of current EVAs and, finally, the use of haptic feedback in space exploration scenarios.

2.1 Sensory Cues & Tacit Knowledge

We define tacit knowledge as non-verbalized, intuitive, and unarticulated knowledge. It is non-declarative knowledge of the world, based on embodied experience, as opposed to explicit, declarative knowledge. For example, declarative knowledge might include how to spell the word "swing"; it is the knowledge we can easily convey to others. This is in contrast to the activity of swinging. While most of us know how to swing, articulating what exactly one needs to do to set a swing in motion is challenging.

Polyani [12] introduced the term "Tacit Knowledge" to describe the ability to do something without being able to articulate how to do it: this includes riding a bicycle or playing a musical instrument, without having the ability to fully explain all details of how it is done. Polyani claims that all practical skills rely upon tacit awareness. We extend this to incorporate knowledge about the world, as this is the foundation of any skill. For example, both riding a bicycle and swinging in a swing require a tacit understanding of physics.

Such tacit understanding of the world is also related to domain-specific knowledge, for example, many technicians rely on auditory and visual cues to detect failure on complex machinery [15]. Another documented case is craftsmen from a renowned Japanese denim brand, who claim that they share a unique bond with their machines, relying solely on auditory cues to calibrate them. This tacit understanding of the machinery is built over time and has been handed down through generations [14]. Research is only beginning to explore making such knowledge explicit, for example, by training machine-learning models to identify acoustic cues for fault diagnosis [17].

In this work, we assume that astronauts have a rich body of tacit knowledge of materiality and physics, which includes understanding vibration feedback, be it tactile or audible, and having the ability to infer what caused it. Our work aims to leverage such knowledge to make EVAs safer and more effective.

2.2 Extravehicular Activities (EVA) Challenges

At the time of this writing, it has been over 60 years since Alexei Leonov floated in free space on March 18, 1965. This event is considered the first human EVA – an activity conducted by an astronaut in outer space outside a spacecraft. EVAs include spacewalks as well as lunar or planetary surface exploration, such as moonwalks. According to a 2004 NASA report [5], in the four decades following Leonov's EVA, humans spent approximately 900 hours in microgravity and over 160 hours on the lunar surface performing EVAs. The same report highlights the following key areas for improvement in future EVAs: (1) all subsystem designs should prioritize simplicity and reliability based on fundamental principles, favoring these over added functionality in case of trade-offs; and (2) methods are needed to support and maintain high levels of mental performance during EVAs.

Conducting EVAs is extremely mentally challenging. A large part of EVA training focuses on cognitive preparedness, often described as "putting on your EVA brain." Success relies heavily on planning actions and movements in advance [4]. Several factors contribute to these challenges. For example, vibration and auditory cues are absent in the vacuum environment. Additionally, bulky suits constrain movement and act as sensory insulators. The design of current space suits – ranging from 10 to 30 mm in thickness and composed of up to 16 layers – significantly reduces both audible and tactile feedback [8]. These limitations impair the astronaut's ability to perceive non-visual cues, grasp objects, and maintain proprioception. As a result, cognitive performance can decline, increasing the risk of accidents [15].

In contrast, access to sensory feedback has been shown to improve task performance and reduce cognitive load in complex environments [16, 9]. Based on this, researchers have explored ways to reintroduce sensory input in space contexts. For example, Berengueres [2] demonstrated that enabling sound transparency during Intravehicular Activities (IVAs) can mitigate sensory deprivation and improve cognitive performance. However, their approach requires complex instrumentation of the astronaut's environment.

We propose the vibroLink concept as a way to enhance sensory access and improve situational awareness during EVAs. The system provides EVA pilots with a means to leverage their tacit material knowledge and supports sustained high-level mental performance.

The vibroLink units will be designed to operate fully standalone, adhering to the principle that subsystem designs should prioritize simplicity and reliability. Keeping the units independent avoids the complexity of integration with other systems.

2.3 Haptics in Space Exploration

Hearing and vision are distal senses – we perceive objects that are located away from the body. According to Katz, touch is different in that it involves both distal and proximal aspects [7]. For example, when we feel the rumbling of a machine, we perceive something that originates at a distance. But unlike hearing and vision, touch also has a proximal aspect: when we touch a material, we perceive the stimulus directly on the skin, at the point of contact.

The extreme conditions of space significantly limit direct physical interaction, restricting astronauts' ability to perceive their environment, be it distally or proximally. To address this challenge, researchers have been exploring the development of haptic feedback systems.

These systems aim to enhance interactions by providing tactile sensations. Their goal is to bridge the sensory gap created by the harsh extraterrestrial environment and the limitations of current spacesuit technology.

There is a large body of research on improving textiles for space exploration (e.g., [3]), which includes space suits with integrated tactile feedback [11]. The suit proposed by Wicaksono uses various sensors, such as piezoelectric and conductive fabrics, to detect external tactile cues. It then relays this information to the astronaut's skin through vibration motors, creating dynamic tactile experiences that correspond to the materials outside the suit [11]. Similarly, ExoSkin is a proposed haptic layer for the space suits' gloves. This layer would allow haptic cues from the external environment to be transferred to the astronaut's skin using small free-moving pins. These pins adapt their shape based on surface contact, providing haptic feedback to the fingertips [13].

Existing systems are aimed at augmenting proximal tactile perception. Our approach aims to enhance sensory access to remote locations. Placing a patch on a solar panel, provides an EVA pilot with a distal experience of the vibration conditions at that panel.

In addition to the system aiming to augment a different type of experience, existing systems also have the drawback of requiring complex integration with future space suits. Our vibroLink concept, however, is designed to seamlessly augment existing EVA equipment, without requiring complex technological integration.

3 Envisioned Scenario

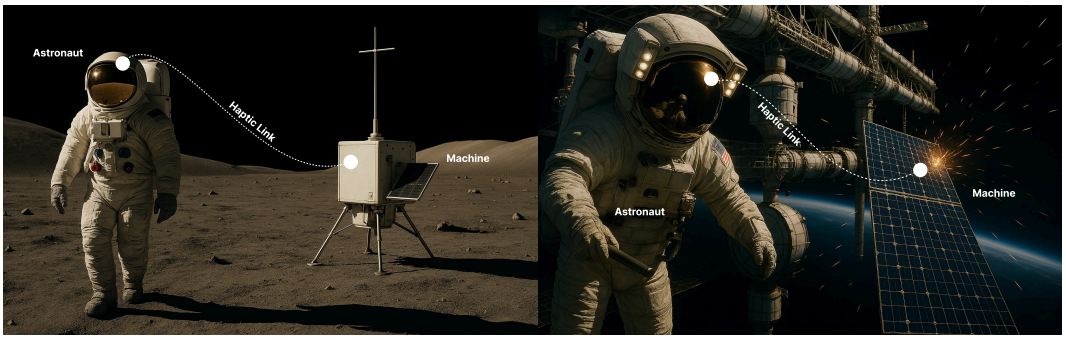

Figure 1 Envisioned scenarios for the vibroLink system include practical applications such as monitoring machine status remotely during repairs or detecting micro asteroid collisions during solar panel maintenance. *Notice: The images were generated by AI.*

We envision vibroLink being used during EVAs to improve situation awareness and facilitate machinery repair for astronauts. The system consists of two components: a receiver and a transmitter. As the astronaut performs machinery repair or maintenance and needs to monitor the status of a particular machine or surface, they can simply attach the transmitter unit to the chosen surface and the receiver unit to their helmet. This will vibrate the air inside the helmet, enabling the perception of the sensed vibration. The sensing unit will automatically transmit vibration data from the surface to the helmet as the astronaut continues with the proposed EVA plan. This vibration data can be used to assess the condition of the machinery and identify any problems or abnormalities, such as impacts, or strain.

3.1 Scenario 1 - Space Station Repair

The astronaut leaves the space station through the airlock and carefully maneuvers along the exterior using handrails for locomotion and security. Upon reaching the solar panel area, they attach their tether for safety. The astronaut performs a visual inspection to look for any visible damage. They check the joints and electrical connections, making adjustments or repairs as needed.

Here the astronaut might attach a transmitter unit to the base of the tether, so that they are aware of any mechanical problems with the tether.

3.2 Scenario 2 - Assembly of a Satellite

Two astronauts exit the spacecraft, carrying satellite components and required tools. They move toward the assembly location – first using tethers and handrails, then with astronaut #1 operating a robotic arm to position astronaut two correctly. Astronaut #2 begins by aligning the satellite's base with its mounting structure and securing it with bolts or clamps. One by one, they attach additional components such as antennas or sensors, while astronaut #1 adjusts their position relative to the satellite using the robotic arm. After each connection is checked for proper fit and stability, the astronaut powers up or tests parts of the satellite.

Here, astronaut #1 might request astronaut #2 to place a transmitter unit on the satellite itself, allowing astronaut #2 – equipped with a receiver unit – to gain better sensory access to the ongoing assembly process. Additionally, astronaut #2 may place a transmitter unit on the robotic arm's motors. Since the arm is frequently used to change position, this setup helps them distinguish whether relative motion between themselves and the equipment is caused by drift or by the arm's movement.

3.3 Scenario 3 - Soil Probe collection

The astronaut exits the planetary lander and steps onto the moon's surface. Moving slowly and carefully, they walk toward a designated location for sample collection. Upon arrival, they unpack a probe tool from their equipment, insert it into the ground, and collect a soil sample. Once the task is complete, the sample is secured in a storage container.

In this scenario, the astronaut might attach a transmitter unit to a piece of machinery inside the lunar lander. The purpose of vibroLink here is not strictly utilitarian. In the harsh and unfamiliar environment, the familiar vibration pattern from the lander's machinery provides a sense of comfort and orientation. It offers the astronaut a subtle but reassuring cue that their way back home is secure, even if the lander is temporarily out of sight, and supports their emotional wellbeing.

4 Implementation

The vibroLink system is designed to be a simple yet efficient tool for deployment during EVAs. It compromises two main components: a receiver unit and a transmitter unit (see Figure 2), each equipped with an adhesive backing for effortless attachment to different surfaces or equipment. This section provides an overview of the system.

The transmitter unit features a generic piezoelectric sensor that detects surface vibrations in real-time. Piezo electrics sensors are well-suited for this purpose, offering exceptional tolerance to extreme temperatures, as well as high sensitivity and resolution, making them ideal for measuring vibrations in spacecraft [6]. The transmitter unit also incorporates a PAM8302 amplifier and an off-the-shelf AirBorne Wi-2.4-GHz Bluetooth transmitter module.

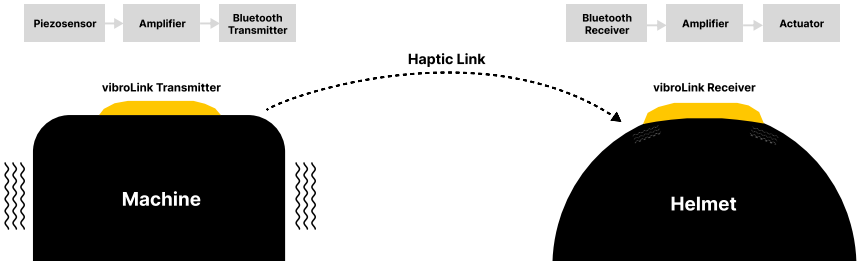

Figure 2 The vibroLink system.

Meanwhile, the receiver unit – designed to be affixed to an astronaut's helmet – includes an off-the-shelf AirBorne Wi-2.4-GHz Bluetooth receiver module, a PAM8302 amplifier, and a Vybronics VG1040003D Linear Resonant Actuator (LRA) as vibroactuator. This transmitter senses the vibration data from the designated location, treating it as audio data. It is transmitted to the receiver, which plays back the same signal, again treating it as audio. As the system operates in near real time, this enables the astronaut to feel the vibrations as they occur. Both units are intended to be powered by lightweight, thin-film lithium-ion batteries, enhancing their portability and practicality for EVA applications.

5 Evaluation

To assess the usefulness of the information transmitted through basic tactile cues provided by our system, we conducted two preliminary explorations with six participants using the vibroLink prototype. They were aimed at identifying if the system functioned, in principle (Exploration #1), and to understand if participants, without prior instruction, can implicitly identify different materials and actions (Exploration #2).

In each exploration, participants sat on a chair with a receiver unit, their index finger touching the vibroactuator, guided by Experimenter #1. Simultaneously, in a separate room, Experimenter #2 generated various stimuli on the piezoelectric sensor in the transmitter unit.

5.1 Exploration #1: Number of Knocks

Participants were tasked with identifying the number of knocks perceived through the vibroactuator's feedback. Experimenter #2 knocked on the piezo sensor using a rigid plastic piece in a separate room while participants felt the vibratory feedback and identified the number of knocks. Each participant completed one trial, which consisted of four stimuli (1, 2, 3, or 4 knocks) presented in a randomized order.

Participants correctly identified the number of knocks with an overall accuracy of 95.83%. Five out of six participants achieved 100.0% accuracy, while one participant made one error.

5.2 Exploration #2: Discrimination of different materials

Participants were asked to identify both the material and the action conveyed through the tactile feedback. The experiment used two materials (soft and hard) and two actions (scratching or knocking the piezoelectric sensor), resulting in four distinct pairs of stimuli: (soft, knocking), (soft, scratching), (hard, knocking), and (hard, scratching). Experimenter #2

performed the stimuli using a rigid object from Study #1 as the hard material and a piece of sponge as the soft material. Each participant completed one trial in which the four pairs of stimuli were presented in a randomized order. Before the experiment, participants were familiarized with the tactile feedback of all four combinations once.

Results showed an overall accuracy of 87.50% in identifying the stimuli. Four participants achieved 100% accuracy, while P1 misidentified a material, and separately P2 misidentified a material and an action.

5.3 Discussion

Current EVA operations rely heavily on visual information. The bulkiness of EVA suits and the vacuum of space shield astronauts from the vibrations of their surroundings. However, these vibrations are important to our tacit understanding of materiality and actions. vibroLink addresses this problem by offering an implicit, continuous information stream that can operate in parallel with visual tasks. Our preliminary evaluations indicate that such a link can indeed be used to transmit tacit information. Untrained participants were not only able to decode explicit tactile signals such as the number of knocks, but also to differentiate between materials and actions through vibration alone. This suggests that the information provided by vibroLink can effectively support a better understanding of one's environment during EVA activity.

A system such as vibroLink likely has other benefits related to EVA operations. A central issue during EVA is sensory deprivation due to the isolation provided by the space suit, which can degrade cognitive performance and increase the risk of errors. Our system may mitigate such cognitive effects by increasing sensory access to the astronaut's environment.

A common concern identified in the literature is the potential complexity of integrating haptic feedback systems into existing suits – generally, added functionality is seen as something that may compromise the safety and reliability of equipment. Many proposed solutions require extensive integration with existing technology stacks. We avoid this issue by proposing that vibroLink operate independently, requiring no integration with existing subsystems. Furthermore, the components are deployable ad hoc and can be integrated into deployment procedures and best practices. This simplicity directly responds to the requirement that EVA tools prioritize reliability and ease of use.

Despite its promise, our prototype still faces technical limitations. The piezo sensor in the transmitter lacks sensitivity to low-frequency vibrations, which we have found important for detecting subtle mechanical anomalies. This limits the system's applicability for more complex diagnostic tasks. We propose combining the piezo sensor with an accelerometer to expand the frequency range, though this introduces new challenges in signal fusion and actuation algorithms that will need to be addressed.

Additionally, testing with expert users and under more realistic conditions is necessary to validate the system's relevance in situ. Open questions include whether vibroLink requires any form of longitudinal training for astronauts to fully benefit from it, and whether there are conditions under which the information it provides could be perceived as distracting rather than helpful. Another consideration is whether the current one-to-one transmitter–receiver pairing should be maintained – with all its benefits for creative deployment – or upgraded to a multi-sensor system connected to a single receiver, which may be less flexible but better suited for certain tasks.

In sum, vibroLink offers a lightweight, flexible, and cognitively compatible solution to well-documented EVA limitations. By reintroducing tactile cues through a standalone, easily deployable system, vibroLink addresses both technical and cognitive challenges identified in prior work, and opens a path toward more embodied interaction in extreme environments.

6 Conclusion

This paper introduced vibroLink, a concept and initial proof-of-concept prototype of a wireless vibro-auditory transmission system designed to enhance situational awareness and facilitate machine repairs during EVAs. This system enables astronauts to wirelessly receive tactile cues from various sources, such as machines or surfaces, allowing them to detect possible failures or critical environmental changes during EVAs.

The system is designed to operate independently of existing EVA infrastructure, meaning it does not require complex and potentially costly integration with other systems. It consists of two units: a transmitter that can be attached to any surface or machinery, and a receiver unit intended to be mounted on the astronaut's helmet.

We tested a proof-of-concept prototype vibroLink in two explorations, which confirmed its functionality in transmitting basic tactile cues and that naive users can leverage their tacit understanding of actions and materiality to identify how the cues originated.

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Toward an Earth-Independent System for EVA Mission Planning: Integrating Physical Models, Domain Knowledge, and Agentic RAG to Provide Explainable LLM-Based Decision Support

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Abstract

We propose a unified framework for an Earth-independent AI system that provides explainable, context-aware decision support for EVA mission planning by integrating six core components: a fine-tuned EVA domain LLM, a retrieval-augmented knowledge base, a short-term memory store, physical simulation models, an agentic orchestration layer, and a multimodal user interface. To ground our design, we analyze the current roles and substitution potential of the Mission Control Center – identifying which procedural and analytical functions can be automated onboard while preserving human oversight for experiential and strategic tasks. Building on this framework, we introduce RASAGE (Retrieval & Simulation Augmented Guidance Agent for Exploration), a proof-of-concept toolset that combines Microsoft Phi-4-mini-instruct with a FAISS (Facebook AI Similarity Search)-powered EVA knowledge base and custom A* path planning and hypogravity metabolic models to generate grounded, traceable EVA plans. We outline a staged validation strategy to evaluate improvements in route efficiency, metabolic prediction accuracy, anomaly response effectiveness, and crew trust under realistic communication delays. Our findings demonstrate the feasibility of replicating key Mission Control functions onboard, enhancing crew autonomy, reducing cognitive load, and improving safety for deep-space exploration missions.

2012 ACM Subject Classification Human-centered computing → Interactive systems and tools; Human-centered computing → Interaction design process and methods

Keywords and phrases Human-AI Interaction for Space Exploration, Extravehicular Activities, Cognitive load and Human Performance Issues, Human Systems Exploration, Lunar Exploration, LLM

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1 Introduction and Background

Current extravehicular activity (EVA) sorties are highly choreographed and rely on continuous support from ground control teams [5][6][33]. Flight controllers in Mission Control meticulously monitor the astronauts' suit telemetry and progress during EVA, managing safety and tasks in real time[33][39]. While this Earth-dependent model is feasible for current International Space Station (ISS) and lunar EVAs, future lunar habitats and surface infrastructure will necessitate multiple concurrent EVAs, and Mars missions will face significant communication latency and limited bandwidth[33][34][9]. Past missions have highlighted the challenges in on-the-fly EVA decision-making. For example, Apollo 14 astronauts attempted to reach Cone Crater without real-time navigation aid and had to abort when they became

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disoriented and fatigued, despite coming within approximately 40 meters of the rim[32]. They carried only a paper map and made judgments on the ground while mission control tracked their vital signs[32]. This incident underscores the need for Earth-independent autonomous planning, monitoring, and decision-making support during EVAs.

NASA's Personalized EVA Informatics & Decision Support (PersEIDS) initiative represents an important step toward autonomy by leveraging the Crew State & Risk Model (CSRM) to project individualized crew health and performance parameters – such as metabolic rate, thermal load, fatigue, CO_2 dose, and decompression stress – over EVA timelines [35][1]. PersEIDS develops user interfaces, visualizations, and data-science methods that deliver actionable, data-driven options and recommendations to extravehicular and intravehicular crewmembers for safe, efficient planning and execution under high-latency conditions [35]. It also automatically tracks and probabilistically assesses suit consumables against flight rules to improve mission completion time and preserve consumables relative to unsupported operations [35]. However, while PersEIDS excels at biomedical decision support and consumable management, it does not provide end-to-end task planning, context-aware reasoning, or the fully autonomous "virtual flight controller" functionality needed when ground support is delayed or unavailable. Moreover, a fully autonomous decision-support system can directly interpret CSRM's predictive outputs, streamlining EVA planning without adding crew cognitive workload.

To fill this gap, an autonomous, Earth-independent artificial intelligence (AI) system – integrated within spacecraft, habitats, or embedded directly in astronaut suits – is envisioned by acting as a local "virtual flight controller" for the crew. Such a system could enhance astronaut safety and efficiency by dynamically replanning routes, monitoring astronaut health, providing task-related information, and advising the crew immediately, rather than waiting for delayed input from Earth. This can optimize EVA outcomes in real time, reducing reliance on ground support. Recent technological advancements underscore the feasibility of deploying sophisticated Large Language Models (LLMs) in space. In mid-2024, Booz Allen Hamilton, in collaboration with Hewlett Packard Enterprise (HPE), successfully deployed an LLM retrieval-augmented generation (RAG) application aboard the ISS using HPE's Spaceborne Computer-2 to help perform certain maintenance and repair procedures [17]. This milestone demonstrated that disconnected AI operations in austere environments are achievable.

In this paper, we introduce a framework for an Earth-independent AI system for EVA mission planning and decision support that integrates: (a) a small-parameter EVA domain LLM fine-tuned on astronaut-ground transcripts, NASA EVA handbooks, flight rules, and related literature; (b) a retrieval-augmented knowledge base of procedures, checklists, operational logs, and related documents; (c) a suite of physical simulation models (path planning, metabolic prediction, thermal load, radiation dose, life-support performance, communications quality, power consumption, and more); (d) a short-term memory store that persistently captures mission context (objectives, timeline), crew profiles (roles, expertise, health/status), prior user–agent interactions, and live sensor telemetry; (e) an agentic orchestration layer that sequences semantic retrievals, model invocations, ReAct-style iterative reasoning, and generation into fully traceable, explainable EVA recommendations; and (f) a multimodal user interface (text, voice and visual) that delivers concise guidance, annotated maps, task timelines, and underlying rationale with source citations. Building on this framework, we introduce RASAGE (Retrieval & Simulation Augmented Guidance Agent for Exploration), a proof-of-concept toolset that implements these components to deliver context-aware, quantitatively grounded decision support – emulating key Mission Control functions, enhancing

crew autonomy, and safeguarding astronaut safety when Earth support is delayed or unavailable. This paper provides a high-level review of relevant literature, outlines our proposed architecture and experimental plan, and discusses associated risks and future steps toward realizing this vision.

2 Current Roles and Substitution Potential of Mission Control Center

The Mission Control Center (MCC) serves as the operational hub for space missions, providing critical support across multiple domains [24]. For EVA operations specifically, MCC fulfills several essential functions that must be considered when designing an Earth-independent alternative. These functions include managing EVA timelines, tracking suit telemetry and consumables, providing contingency guidance during off-nominal situations, conducting real-time risk assessment and decision-making, optimizing resource usage, delivering specialized scientific guidance, coordinating communication between the crew and ground teams, monitoring astronaut physiological and behavior health, and strategically adjusting mission plans in response to discoveries or unexpected challenges [38][39][37][41][40][25][15]. Given these roles, what could be substituted with an onboard AI agent? The potential for substituting these functions with automated systems or alternative technologies is closely tied to the nature of the knowledge they require. The knowledge types employed by MCC can be categorized as:

- **Procedural Knowledge:** Formalized processes, checklists, and operational sequences documented in NASA handbooks and flight rules.
- **Experiential Knowledge:** Expertise developed through years of mission operations, including pattern recognition and analogical reasoning applied to novel situations.
- **Analytical Knowledge:** Quantitative assessment capabilities for system performance, environmental conditions, and mission constraints.
- **Domain-specific Knowledge:** Specialized expertise in areas such as geology, medicine, engineering, or other disciplines relevant to mission objectives.
- **Strategic Knowledge:** High-level mission planning capabilities that consider multiple interdependent factors and long-term consequences.

Tasks characterized by procedural and analytical knowledge – those governed by well-defined steps, rules, or data-driven logic – are generally more amenable to automation or delegation to technological systems. Conversely, tasks that depend heavily on experiential and domain-specific knowledge, such as those requiring nuanced judgment, intuition, or expertise developed through practical experience, pose greater challenges for automation [4]. Consequently, functions predominantly rooted in procedural or analytical knowledge exhibit a higher potential for substitution, while those reliant on experiential or strategic expertise demonstrate a medium substitution potential. Additionally, the psychological support function demonstrates limited substitution potential. Despite advancements in artificial intelligence, the nuanced interpretation of complex emotional signals, empathetic communication, and personalized adaptation to individual psychological requirements remain predominantly within the expertise of human professionals. Therefore, automated systems should be viewed primarily as supportive tools rather than comprehensive replacements in this deeply human-centered function [27]. This analysis highlights the potential to substitute many functions of the current Mission Control Center (MCC) with automated systems, particularly those rooted in procedural and analytical knowledge. However, it also reveals limitations in fully replacing tasks that demand advanced cognitive, contextual, and emotional capabilities. Table 1 provides a summary of the current functions of MCC and their substitution potential for EVA operation specifically.

Table 1 This table categorizes MCC responsibilities during EVAs and assesses their potential for AI substitution[38][39][37][41][40][25][15].

Function	Description	Knowledge Type	Substitution Potential
Procedure Management	Tracking EVA timeline, providing step-by-step guidance, managing deviations	Procedural	High
Systems Monitoring	Tracking suit telemetry, consumables, and environmental parameters	Analytical Procedural	High
Contingency Response	Providing troubleshooting guidance for off-nominal situations	Experiential Procedural	Medium
Risk Assessment	Real-time evaluation of mission risks and go/no-go decisions	Experiential Analytical	Medium
Resource Optimization	Managing consumables usage and recommending pace adjustments	Analytical	High
Scientific Guidance	Providing expertise on sample collection and experiment protocols	Domain-specific	Medium
Communication Coordination	Managing communication between EVA crew, vehicle crew, and ground	Procedural	High
Medical Monitoring	Assessing astronaut vital signs and health status	Analytical Domain-specific	Medium
Strategic Replanning	Substantial timeline modifications due to discoveries or failures	Experiential Strategic	Medium
Psychological Support	Monitoring astronaut psychological state, providing emotional support, and mitigating stress-related risks	Experiential Domain-specific	Low

3 Evolution from Text Generation to Agency

LLMs have evolved rapidly from early transformer-based models like BERT [13] to sophisticated systems like GPT-o1 [44], with capabilities extending far beyond text generation. This evolution has been marked by key innovations in both model architecture and application techniques. Recent advancements have transformed LLMs from passive text generators into systems with agent-like capabilities. These include self-reflection and output critique [51][31], effective use of external tools and APIs [50][45][56], complex task planning and decomposition [57][55], and multi-agent collaboration through structured dialogues [11][49]. Collectively, these developments enable LLMs to operate as increasingly autonomous, goal-directed systems.

Several key approaches have proven effective for domain-specific applications:

- **Domain Adaptation and RAG:** Fine-tuning on specialized corpora [18] and retrieval augmentation [30] enable LLMs to access and incorporate domain expertise.
- **Reasoning Enhancements:** Techniques like instruction tuning[60] and chain-of-thought reasoning [55] improve models' ability to follow constraints and demonstrate explicit reasoning.
- **Efficiency Optimizations:** Small-parameter models reduce computational requirements while maintaining performance on specialized tasks, making deployment possible in resource-constrained environments [47].

In space applications, these advances have enabled a spectrum of notable implementations. Mission support systems have seen early deployments through CIMON, an ISS-based AI assistant designed to reduce crew workload through natural dialogue [3], and NASA's Callisto experiment, which validated a voice assistant capable of handling procedural queries without Earth communication [16]. Autonomous decision support capabilities advanced significantly with the successful 2024 deployment of a generative AI system with RAG capabilities on ISS, validating the technical feasibility of operating advanced AI within space hardware constraints [17]. Meanwhile, an AI4U assistant – with a capability of learning new skills during operation as a result of its reinforcement learning approach – is being tested in the Mars Desert Research Station (MDRS) facilitates [42] [7]. More recently, CORE (Checklist Organizer for Research and Exploration) and METIS (Mars Exploration Telemetry-Driven Information System) have been proposed as offline-capable intelligent personal assistants that integrate knowledge graphs, retrieval-augmented generation, and augmented reality to deliver reliable, flexible, and intuitive procedural guidance for astronauts aboard the ISS, the Lunar Gateway, and future deep-space missions[7][8]. These developments collectively demonstrate the utility of AI and LLMs across multiple operational domains in space exploration.

It's important to note that baseline LLMs have limitations that must be addressed for mission-critical use. They are prone to hallucination – confidently stating incorrect information – which is unacceptable when astronaut safety is on the line [21]. They also lack up-to-date awareness of the world beyond their training data cutoff. To mitigate these issues, the current state of the art uses Retrieval-Augmented Generation (RAG) and related techniques. RAG involves retrieving relevant documents or facts from an external knowledge source and feeding that into the LLM during query answering [58]. In our context, that means when the astronaut asks the AI a question (e.g., "What's the next step? My CO_2 level is high."), the system would fetch pertinent information (for example the CO_2 scrubber malfunction procedure from the EVA manual, or a rule about terminating EVA upon high CO_2), and the LLM would incorporate that into its response. This approach keeps answers grounded in authoritative sources and reduces the chance of the AI *"making stuff up"*. In NASA's own research, integrating RAG has been shown to improve the feasibility and correctness of LLM-generated solutions in a domain task [54].

The requirements for explainability, robustness to unexpected inputs, and operation within tight computational constraints still pose challenges in developing LLMs in safety-critical space applications. Astronauts must understand AI recommendations sufficiently to evaluate them in high-stakes situations, which require an appropriate level of trust and accuracy of information provided. Current LLM implementations, even those enhanced with basic RAG capabilities, fundamentally fail when confronting problems requiring precise analytical computation or physical simulation. These limitations are especially pronounced in EVA contexts where accurate metabolic modeling, dynamic path optimization, and physical environmental interactions demand capabilities beyond text generation and retrieval alone. Standard language models cannot effectively perform the mathematical modeling, spatial reasoning, or physical predictions needed for critical EVA parameters such as oxygen consumption rates, thermal regulation, or optimal traversal planning across variable terrain. To address these limitations, the agentic RAG paradigm extends the traditional framework by embedding an AI agent capable of orchestrating a sequence of actions. In this pipeline, the LLM is not merely a passive answer generator; it actively plans and executes multiple retrievals, engages external tools (such as a path planner, or other physical simulation APIs) and iteratively refines its reasoning [10]. For example, an EVA planner agent could break down a task, namely planning a route from point A to B, into a series of deliberate steps:

retrieving the mission map and constraints, invoking a path planning module to identify possible routes, consulting a metabolic cost prediction model to estimate oxygen usage, checking predefined procedures and rules, and finally comparing options against safety limits to produce a recommendation complete with explanations. Recent surveys highlight that this agentic RAG approach offers unparalleled flexibility and context-awareness, enabling dynamic retrieval strategies and multi-step reasoning that mirror the decision-making processes of a human flight controller [52]. We aim to leverage these benefits in the EVA domain, effectively creating a digital assistant that can think through an EVA plan similarly to how a human flight controller would – by consulting manuals, running calculations, and deliberating over options.

4 Proposed Framework and Toolset

The framework we propose consists of several integrated components to create a system that provides decision support comparable to Earth-based mission control while operating within the constraints of deep-space missions. An architectural schematic is presented in Figure 1. These components include:

- **Fine-Tuned EVA Domain LLM**: A language model (with relatively small parameters for on-board deployment) that has been fine-tuned on a corpus of EVA-related text. This includes transcripts of astronaut-ground conversations, EVA procedure documents, NASA operations handbooks, flight rules, and relevant academic literature. The fine-tuning process imbues the LLM with domain-specific vocabulary and an understanding of the structure of EVA activities. This LLM serves as the reasoning and language generation engine of the system – it will produce explanations, summaries, and recommendations in understandable terms. Crucially, it will not rely solely on its internal knowledge but will use the following modules to ground its outputs.
- **Retrieval-Augmented Knowledge Base (RAG Module)**: A database of EVA knowledge that the LLM agent can query as needed. This knowledge base could be implemented as a vector-indexed document store containing segmented texts from manuals, checklists, plans, and previous EVA logs. When the agent faces a question or task, it can perform a semantic search to fetch relevant snippets. Those snippets are then fed into the LLM's context window so that its decisions and responses cite actual references. The design ensures that even if the LLM's training data is outdated or if it "forgets" a detail, it can retrieve the latest ground-truth information. This is key for explainability – the AI can provide answers directly grounding its advice in source material.
- **Physical Simulation Models (Tool Use)**: A suite of domain-specific physical models that the LLM agent can invoke as needed via standardized APIs. Each module encapsulates a discrete aspect of EVA logistics – such as path planning, metabolic prediction, thermal load, radiation dose, suit life-support performance, communications link quality, and battery consumption – and returns quantitative metrics (e.g., distance, elevation gain, estimated O_2 usage, cumulative radiation exposure, power draw). When the agent evaluates a proposed EVA plan or contingency, it issues a structured query to the relevant model(s). The returned outputs are then incorporated into the LLM's context window so that recommendations are grounded in up-to-date, physical data. This modular approach ensures that the AI's reasoning is both objective – comparing candidate plans across multiple safety and performance dimensions – and explainable, since each decision point can be traced back to concrete model outputs rather than inferred solely from language patterns.

- **Agentic Orchestration Layer**: The central coordination engine that seamlessly integrates the components mentioned above into a unified decision-making workflow with four specialized agents – planning, retrieval, ReAct, and generation. The planning agent first defines task objectives and determines which information and simulations the LLM requires to address a given EVA scenario. The retrieval agent then performs semantic searches of the knowledge base for authoritative procedure snippets and invokes the appropriate physical models to generate quantitative metrics. The ReAct agent (Reason-and-Act) iteratively evaluates retrieved documents and model outputs against safety constraints and mission rules, refining queries or plan steps as needed to close any information gaps; and the generation agent synthesizes the validated context into a concise, actionable recommendation – complete with clear rationale and source citations. This layer ensures that each plan or contingency is grounded in up-to-date textual guidance, domain knowledge, and physical evidence, while logging each intermediate step for auditability and verification.
- **Short-Term Memory Store**: A rolling buffer that continuously captures and organizes critical contextual information – including overall mission objectives and timeline, individual crew profiles (roles, expertise, current health/status), the history of prior user–agent exchanges, and real-time sensory inputs (e.g., suit telemetry, environmental sensor data). This memory module supplies the Orchestration Layer with up-to-date situational awareness and conversational continuity, ensuring that every planning cycle, retrieval query, and recommendation remains consistent, personalized, and aligned with the evolving EVA context.
- **User Interface**: A multi-modal interaction layer that enables astronauts to seamlessly engage with the AI toolset via voice commands and/or a visual display (tablet or helmet HUD). Designed for hands-busy, high-noise EVA environments, the voice interface supports natural language queries and delivers spoken recommendations, while the visual display presents concise, contextually relevant information – such as annotated maps, task timelines, and highlighted procedure snippets. All outputs include clear rationale and source citations (e.g., flight rule references or model outputs) to ensure transparency and foster user trust. The interface dynamically adapts its presentation based on task urgency and crew workload, surfacing only the most critical information during high-stress scenarios and offering deeper explanatory detail when time permits.

Fine-tuning strategy and data availability

Within the proposed framework, the domain LLM will be adapted through a two-step, resource-aware pipeline: (i) task-adaptive pre-training (TAPT) on the full raw EVA corpus, approximately 18 M token outlined in Table 2, to familiarise the backbone with mission-specific vocabulary and discourse [18], and (ii) parameter-efficient QLoRA fine-tuning on a carefully curated dataset of several thousand question–answer pairs, inserting low-rank adapters while the 4-bit base weights remain frozen [12]. Source PDFs are processed with olmOCR, which converts each page image into clean, ordered text, removes noise, and drops duplicates before embedding [48]. The cleaned corpus will be also segmented, embedded, and stored in the Retrieval-Augmented Knowledge Base to ensure that training and real-time grounding reference the same documents. LoRA/QLoRA studies demonstrate that models in this parameter range can achieve substantial gains from just a few thousand high-quality instruction–response examples [22][59]; therefore, our curated Q&A dataset fully supports effective fine-tuning. All sources are public-domain U.S. Government works. This workflow

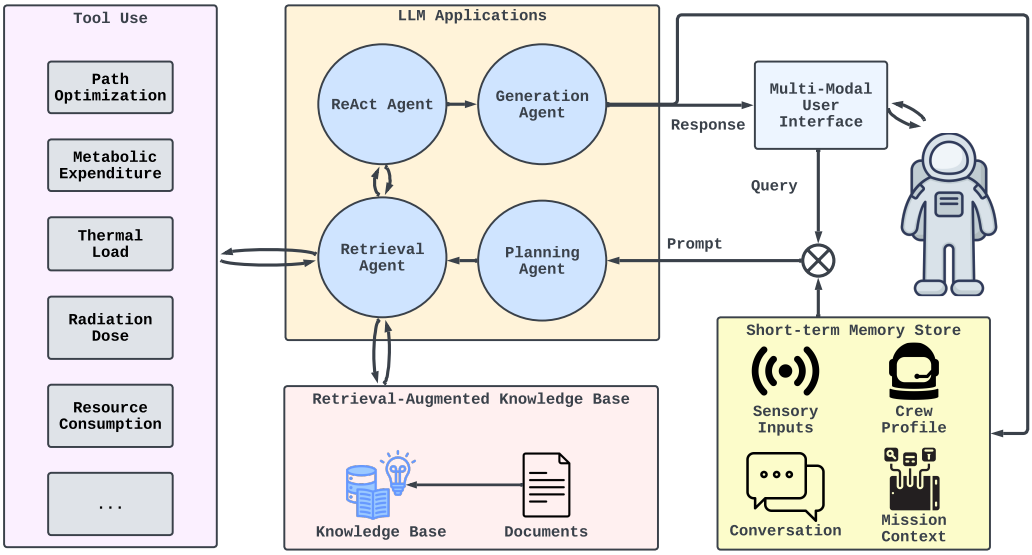

Figure 1 Conceptual Architecture of the AI EVA Planner.

minimizes on-orbit compute demands and allows future document updates to be re-embedded and adapter-patched without modifying the frozen backbone, preserving consistency across the integrated framework.

Physical-Simulation Suite

Each physics model is encapsulated as a uniform JSON-RPC endpoint that the LLM can invoke on demand [26]. The exemplar modules listed in Table 3 – the path planner, the hypogravity metabolic-cost model, the thermal-load and radiation-dose estimators, and the suit-consumables tracker – are drawn from literature with extensive prior studies demonstrating their suitability for seamless integration. For every call, the agent submits a compact JSON request and receives a structured reply that returns hard numbers (e.g., way-points, ascent, ETA, $\dot{V}O_2$, coolant margin, O_2). Each request–response pair is logged, routed through downstream checks, and ultimately surfaced to the crew with full parameter context, yielding an auditable *retrieve* $\rightarrow$ *compute* $\rightarrow$ *evaluate* loop. Because the framework is inherently versatile, additional or higher-fidelity simulators can be added at any time by exposing the same endpoint schema, allowing the toolset to grow without altering the surrounding architecture.

Concept of Operations

In operation, the proposed AI toolset would support EVA mission planning at every stage – from high-level strategy during pre-mission planning to dynamic decision support in real time. During mission planning, astronauts and flight planners can simulate multiple EVA scenarios, asking "what if" questions such as "What if we add a geology stop here – can we still return to the lander in time given our oxygen reserves and estimated metabolic expenditure?" to refine task sequences and resource allocations. Once on the surface, the system helps brief and verify the day's EVA plan, enabling the crew to request a final check – "Are all tasks feasible within a six-hour EVA given current consumables and predicted metabolic

Table 2 Summary of Extravehicular Activity Document Corpus (token counts estimated using the conservative heuristic of 250 words per page and 1.3 tokens per word[53][43]).

Document Set	Pages (approx.)	Words ($\times 10^3$)	Tokens ($\times 10^3$)	Source
NASA Mercury–Apollo–Gemini Communications Transcripts	46,000	11,500	15,000	NASA JSC History Collection
EVA Console Handbook & Flight-Control Operations Manual	1,800	450	585	JSC-26843 JSC-29229 JSC-20597
Apollo & Space Shuttle & ISS Flight Rules	5,000	1,250	1,625	NSTS-12820 Apollo 8 - 17 Final Flight Mission Rules
Exploration EVA System Concept of Operations & Technical Standards	200	50	65	EVA-EXP-0042 EVA-EXP-0034
NASA Technical Standards (Human Factors and Health)	900	225	290	NASA-STD-3000 NASA-STD-3001
EVA Tools and Equipment Reference Book	750	190	250	JSC-20466
xEMU Data Book	600	150	195	JSC-E-DAA-TN55224
Selected EVA technical library documents (roadmaps, analog debriefs, etc.)	1,600	400	520	NASA EVA Technical Library
Total (approx.)	**57,000**	**14,200**	**18,500**	

load?" – with immediate confirmation or warnings if constraints would be violated. During the EVA, the tool continuously monitors progress: if an astronaut falls behind schedule or deviates from the planned route, the astronauts can ask the AI to recompute the timeline and recalculate metabolic costs for alternative routes to ensure safe return margins. In an anomaly – such as a malfunctioning tool – the AI retrieves step-by-step troubleshooting procedures while simultaneously assessing whether continued work would exceed safe workload or consumable limits, leveraging its embedded metabolic prediction model to advise whether to proceed, adjust tasks, or terminate the EVA. Crucially, all functionality operates offline, providing immediate, explainable guidance even when communications with Earth are delayed or unavailable, while still complementing Mission Control for higher-level decisions when connectivity permits.

5 The RASAGE Project

Currently, we are developing a proof-of-concept toolset named Retrieval & Simulation Augmented Guidance Agent for Exploration (RASAGE). RASAGE is designed as an integrated Earth-independent decision support system that combines a compact on-board LLM with a structured retrieval framework and physical simulation in an agentic RAG pipeline. Its core language component, Microsoft-Phi4-mini-instruct, is an open-source 3.8 billion-parameter model quantized to 4 bits and optimized for small-scale GPUs [2]. We will fine-tune Phi-4-mini on a curated EVA corpus – NASA EVA handbooks, flight rules, astronaut-ground transcripts,

Table 3 Example Physics-Based Simulation Tools.

Module	Inputs	Outputs (per call)
Path planner	Start/goal, DEM tile, slope limits, oxygen constraint	Optimal path, distance, ascent, travel-time, predicted O_2 usage
Hypogravity metabolic-cost model	Speed, grade, suit mass, g	$\dot{V}O_2$, kcal h^{-1}, O_2 usage
Thermal load estimator	Solar angle, wind, suit RL parameters	Skin/core T traces, coolant margin
Radiation dose calculator	SPENVIS pre-computed look-up & shielding depth	mSv per EVA
Suit-consumables tracker	Task timeline, suit power profile	Remaining Wh, O_2, CO_2 absorbent

anomaly reports, and analog mission debriefs. Complementing the LLM is a vector-indexed knowledge base composed of metadata-annotated, semantically segmented document chunks, built using FAISS (Facebook AI Similarity Search) – an open-source library designed for efficient similarity search and clustering of dense vectors[23][14].

In our system, raw EVA documents are converted to plain text and segmented into coherent chunks using a recursive splitting algorithm that preserves procedural structure and context. Each chunk is enriched with detailed metadata (source, section, page, timestamp) for precise traceability, and is transformed into a dense vector representation via Phi-4-mini's embedding head. These embeddings, along with their metadata, are then indexed in a FAISS vector store, enabling rapid semantic searches. During operations, RASAGE performs semantic retrievals of authoritative procedure snippets, grounding every recommendation in up-to-date source material and ensuring full traceability and explainability.

RASAGE's agentic coordination engine orchestrates a seamless retrieval-augmented workflow that integrates both textual guidance and quantitative simulation outputs via standardized function calls. Domain-specific physical modules, including an A*-based path planner [19] over high-resolution lunar digital elevation models (DEMs) and a hypogravity ambulation metabolic prediction model [28], are indexed and fused into the LLM's context window. The resulting recommendations undergo iterative refinement against safety constraints and mission rules, with every decision logged for auditability. A multi-modal interface (text, voice and tablet display) delivers concise, contextually relevant information – complete with clear rationale and source citations – dynamically adapting output detail based on task urgency and crew workload to maximize situational awareness and trust during EVA.

5.1 Experimental Design

To evaluate the feasibility and effectiveness of the proposed AI system, we will first conduct a series of controlled digital simulation experiments in an EVA environment modeling lunar terrain, a physical astronaut model, and a library of representative tasks. The prototype of the digital simulation interface using Apollo 14 EVA scenarios is shown in figure 2. First, we will evaluate route-planning performance by tasking the AI to generate navigation plans under predefined time and resource constraints and comparing its chosen paths, EVA duration, and energy use against baseline strategies (shortest-distance routing and expert-derived plans). Next, we will validate metabolic model accuracy by benchmarking the AI's consumable-usage

predictions (O_2 and battery) against published NASA EVA metabolic data and historical EVA logs [46], quantifying prediction error and iteratively adjusting model parameters until errors consistently fall within predefined safety thresholds.

We will then conduct human-in-the-loop analog trials that simulate off-nominal EVA events (e.g., rising suit CO_2 levels) under realistic communication delays. In these scenarios, we will measure the AI's response latency, correctness of guidance against NASA flight rules, and success in resolving anomalies before Earth-based support could intervene. By comparing paired scenarios with and without the AI assistant, we will quantify impacts on crew task efficiency, error rates, and cognitive workload – demonstrating whether RASAGE maintains or improves EVA performance and safety under deep-space conditions. Additionally, we will log and categorize every participant query to the system, using these data to identify usability gaps and inform iterative interface and capability improvements.

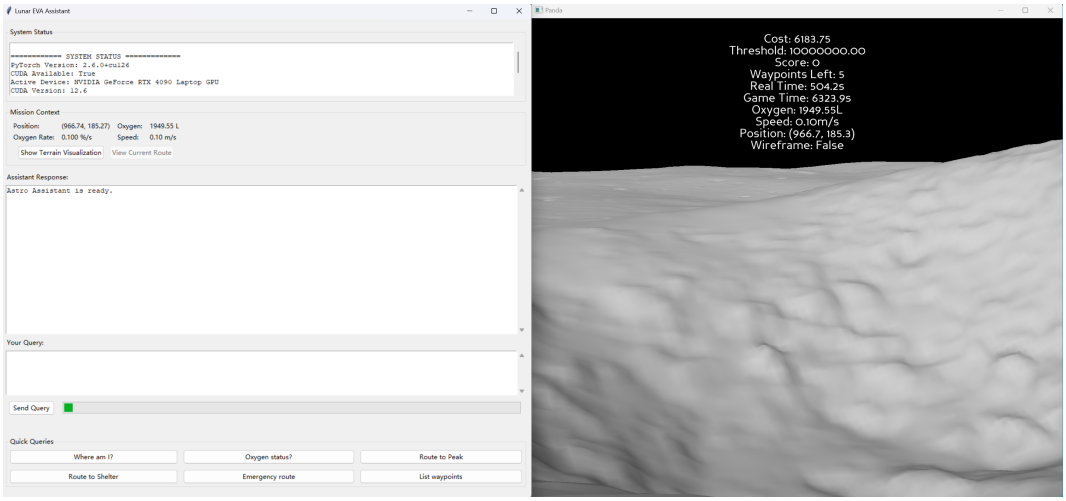

Figure 2 Prototype digital simulation interface in Apollo 14 EVA scenarios, showing the Lunar EVA Assistant's user interface (left) and a 3D lunar terrain visualization (right).

After software validation, our next step is a preliminary field evaluation in a nearby outdoor environment that mimics EVA conditions (e.g., uneven terrain, limited visibility, and communications delay). In this lab-led field test, participants wearing mock-up suit gear will use RASAGE to plan routes, respond to simulated anomalies, and complete task checklists while we measure task completion rates, time to resolution, error incidence, and log every user query for iterative design feedback. Building on these results, we will then propose deploying the system in established analog facilities (including NASA facilities such as Desert RATS, NEEMO, or HERA, and other facilities such as the Mars Desert Research Station Utah, MDRS) during designated "crew-autonomous" EVA days under a 20-minute round-trip communication delay. These higher-fidelity trials will collect both quantitative mission-outcome metrics (objective achievement, anomaly resolution speed) and qualitative insights (usability, clarity, trust) to refine RASAGE's interface, guidance phrasing, and operational integration.

5.2 Evaluation Metrics Summary

Across these experiments, success will be measured by both quantitative metrics (e.g., reduction in excess distance traveled, percentage of scenarios where the AI correctly averts a problem, accuracy of model predictions) and qualitative assessments (crew confidence in

the system, perceived workload reduction, trust in recommendations). We expect the AI to demonstrate measurable improvements in EVA planning efficiency and contingency response. For instance, we aim for a >20% improvement in energy efficiency of routes (compared to baselines) and near-100% compliance with safety constraints (the AI should never violate a known flight rule). Additionally, we'll evaluate explainability: we will survey users on whether they felt the AI's explanations were sufficient and clear. The ideal outcome is that users not only accept the AI's advice but can also articulate why the plan is what it is, indicating successful knowledge transfer from the AI.

5.3 Risk Analysis

Developing and deploying an AI-driven EVA planning system carries several technical and operational risks that must be carefully managed:

- **Reliability & Safety:** LLM hallucinations or incorrect suggestions could jeopardize crew safety. Mitigations include retrieval-grounded responses, strict constraint enforcement, mandatory source citation for safety-critical advice, and a formal verification & validation process analogous to flight-software certification.
- **Scope & Competence:** The AI's knowledge is inherently limited to its training corpus. RASAGE will self-assess uncertainty ("I don't know") and defer novel or ambiguous scenarios to human judgment, with clear documentation of system boundaries.
- **Computational Constraints:** Space hardware has limited processing capacity. We mitigate this by using a quantized Phi-4-mini model optimized for onboard accelerators, designing a modular architecture that isolates faults, and ensuring graceful degradation if simulation modules fail.
- **Human–System Integration:** Trust and usability are essential in EVA operations. The user interface will surface only mission-critical information under high workload, provide transparent rationale for recommendations, and be refined through analog mission testing to prevent information overload.
- **Accountability & Bias:** All agent reasoning steps, retrieved sources, and simulation outputs are logged for post-event auditing. Crew training exercises – both with and without AI assistance – will calibrate trust and mitigate automation bias.

By embedding these safeguards and following established NASA and industry guidelines for trustworthy AI [36][29][20], RASAGE is designed as a support tool that errs on the side of caution and enhances – not replaces – human decision-making.

6 Future Work

Building on the envisioned proof-of-concept system introduced in Section 4, multiple avenues remain for advancing the technical robustness, operational readiness, and domain applicability of RASAGE and similar AI-driven EVA support systems.

- **Extending Simulation Fidelity:** While our initial focus is on path planning and metabolic modeling, the environment can be expanded to include detailed rover integration, robotic assistance, and realistic environmental hazards like regolith dust accumulation or dynamic lighting conditions in crater shadows. Incorporating these additional parameters would refine route optimization and contingency responses to better mirror actual planetary surface operations.

- **High-Fidelity Analog Testing and Crew Training:** Following controlled digital simulations, the next step involves extended field trials in environments such as the NASA NEEMO underwater habitat, Mars Desert Research Station (MDRS), the Desert RATS analog, or the HERA (Human Exploration Research Analog) facility. By subjecting the system to mission-length EVA simulations and real-time anomalies under operational constraints, we can collect user performance metrics and refine interface design, agent orchestration algorithms, and knowledge-base coverage.
- **Coping with Partial or Degraded Data:** EVA telemetry may be noisy or incomplete, particularly in harsh environments. Future versions of the system can incorporate robust sensor-fusion and error correction mechanisms, using Bayesian inference or state-estimation techniques to ensure reliable feed-forward to the LLM and simulation modules. This will help maintain safe operation even with intermittent sensor failures or degraded communications.
- **Adaptive Autonomy Levels:** The system currently provides planning, retrieval, and reasoning capabilities. Ongoing research could explore dynamic adjustments to the "level of autonomy" based on crew workload, mission criticality, and time constraints. This feature would allow RASAGE to operate in a more advisory capacity under normal conditions, yet assume higher authority for rapid decision-making in critical or time-sensitive scenarios when Earth-based assistance is unavailable.
- **Cross-Mission and Cross-Domain Integration:** Many of the functionalities outlined – such as retrieval-augmented guidance, physical modeling, and multi-modal user interfaces – are relevant beyond EVA, potentially assisting with in-vehicle maintenance, habitat operations, or scientific payload management. Expanding the knowledge base to additional mission domains would increase the utility and cost-effectiveness of onboard AI systems.

7 Conclusion

This paper outlines a vision – and an early technical framework – for an Earth-independent, onboard AI system capable of providing real-time decision support during extravehicular activities (EVAs). By combining a large language model fine-tuned on EVA procedures, retrieval-augmented knowledge bases, physical simulation modules, and a lightweight agentic orchestrator, the proposed system seeks to emulate key aspects of ground-based flight-controller expertise directly within the spacesuit. Planned experiments in route optimization, metabolic load modeling, and anomaly response are designed to quantify improvements in crew efficiency, resource management, and operational safety. Initial results from the RASAGE prototype suggest that a self-contained, offline-capable AI tool can successfully manage complex EVA tasks while respecting established flight rules and safety margins.

Transitioning this concept into a flight-worthy capability entails addressing several persistent challenges. Chief among these are ensuring robust performance under uncertain or incomplete data, generalizing across diverse mission architectures, and meeting the rigorous safety, verification, and transparency requirements of human-rated flight software. Despite these hurdles, recent advances in large language models, retrieval augmentation, and physical simulation point toward a future in which onboard autonomy becomes indispensable for deep-space exploration. As crewed missions extend to the lunar surface, Mars, and beyond, Earth-independent AI decision support promises to enhance astronaut safety, maximize scientific return, and reduce dependence on ground control – thereby laying a critical foundation for sustainable human presence beyond low Earth orbit.

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Unbound Human-Machine Interfaces for Interaction in Weightless Environments

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Abstract

User interfaces are subject to the rules of physics (e.g., Newton and Archimedes' laws) relevant to the environment they are in. As such, most interfaces and interaction techniques have been designed for Earth surface. However, when interacting with technology in weightless environments, such as in space, both human and machine will be subject to different physical constraints. For instance, underwater or in Space, people can experience spatial disorientation, which will in turn affect how they use a system. This position paper conceptualizes *unbound Human-Machine Interfaces* (HMIs) as interfaces where either, or both, human and machine are located beyond Earth surface. In particular, it describes how traditional HCI needs to be rethought for interaction in weightless environments and how theoretical models such as joint cognition can support future developments of unbound interfaces.

2012 ACM Subject Classification Computer systems organization → External interfaces for robotics; Human-centered computing → HCI theory, concepts and models; Human-centered computing → Interaction paradigms

Keywords and phrases human-robot interaction, gravity, space, interaction technique

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1 Conceptualizing Unbound Interfaces

Deploying autonomous devices to support humans in their tasks has been a longstanding ambition of scientists across numerous fields. Technological progress and innovations over the last decades have not only brought this vision to life in professional environments where people can now work with devices [42], they have also enabled this in space, such as for astronauts with free-flying robots [7]. In such particular setting, the physicality [31, 47] between human and autonomous devices can be defined as *Unbound*, as the person and device are located beyond Earth surface. We propose that the term can be applied to a larger range of interactions that take place in settings such as in Space or underwater, such as when a robot and diver work together underwater [35]. Such interactions are also possible on Earth when the device is not bound to a surface, as in human-drone interaction where the person is on the Earth surface and the machine is flying [26]. Figure 1 presents examples of such interfaces.

Designing interaction between human and machine is particularly challenging in Unbound contexts as interaction techniques rely primarily on a shared plane of reference, which is unavailable in the Unbound context. For example, prior research showed that the positioning (distance and angle) between human and machine is quintessential to the interaction design [22]. Yet, it does not consider the possibility of movement across all 3 dimensions of space and the constant changes that may occur in such conditions. It also does not take into account differences in friction or in gravity. Similarly, taxonomies of interaction with mobile systems, built around the concept of space and location, did not consider full degrees of freedom between human and machine (e.g., [16]). Yet, these notions are fundamental in Unbound contexts, as for example, the positioning of sensors on the machine and the relative position of a human by the machine will affect the resolution and quality of the resulting interaction – which will simply fail if the user cannot be detected [8]. Similarly, a


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Figure 1 Examples of contexts of use for *Unbound* human-machine interface. Left: Underwater interaction between a diver and a control pad. Middle: People having to control a drone in mountain rescue. Right: Astronaut holding device in open space ©NASA.

person will only see visual feedback on a machine if it is within their visual field, otherwise, the interaction is amiss [30]. In space or underwater, the visual field will often be limited (e.g., using a helmet or goggles) and therefore interaction techniques need to further consider such aspect. Another example is the use of Fitts' Law [19], which has been widely used and adapted for pointing in Human-Machine Interfaces (HMIs) [40, 23], and which relies on Earth physics rules. As such, Fitts' Law cannot be directly applied to Unbound HMIs when the person wants to point and the device to make sense of it, due to issues such as ambiguity, latency, or inertia. This lack of point of reference in Unbound contexts alludes to the fact that standard interaction paradigms that have been established over the last 50 years of research in the field of Human-Computer Interaction (HCI) do not hold beyond Earth surface.

2 From traditional HCI to interaction in weightless environments

HCIs have traditionally been built to support users to interact with technologies on Earth surface. The first user interfaces provided users with input devices such as a mouse and keyboard, and output via visual Graphical User Interfaces (GUI) displayed on a screen [52]. Over the past decades, much research has been conducted and novel multimodal input and output techniques have been proposed, from touchscreens and voice user interfaces in input, to visual, auditory, haptic, or even smell cues in output. Yet, for all of these interfaces, the interaction happens when both the user and the device are within reach of each other, this reach varying based on the modality of interaction, such that a person needs to be within arm's reach to interact with a touchscreen and can be further away from the device in the case of voice input. Several research work have investigated these notions of interaction distances between user and device (e.g., [3, 22, 16]). These models have enabled researchers to go beyond the close interaction that interfaces are traditionally designed for and investigate transitional stages where people become aware of the device, and vice-versa [3, 60, 59], or prepare for the interaction (e.g., adapt to the user [48]). Such research has been fundamental to the fields of HRI in particular, where researchers have been able to develop robots capable of understanding people's needs [56].

In particular, the literature has identified a plethora of criteria that affect the user's experience, such as the appearance of the device [33] or the distance between the device and the person [58]. When focusing on the latter, we find that interfaces are traditionally designed for people to interact at a certain distance from the device, using specific modalities (e.g.,

touch or voice), and enabling people to point or to refer to specific locations that the device can make sense of and calculate based on its own frame of reference. Moreover, research in robotics has shown over the years the importance of proxemics in human-robot interaction [61] proving that when a robot gets too close to a person's body, they can experience discomfort and even withdrawal [41, 53, 13, 30]. This body of work related to interpersonal distancing is based around the notion of proxemics [24]. Preliminary work in human-drone interaction analyzed such proxemics, and showed that the added degree of freedom, indeed affects characteristics of comfortable interaction [62, 18]. As such, a major challenge in Unbound contexts will be to understand how 3D positioning affects human-machine interactions and which mechanisms can be used to mediate interaction distances. It is important to highlight that many additional constraints will affect users in space, e.g., whether they are located inside a vessel or not. Here, we propose to focus entirely on aspects linked to the physics of the environment.

As Unbound interfaces become a reality, we find that the proposed interaction metaphors, concepts, and paradigms are not adapted for interaction with the added degrees of freedom. As such, there is a need to entirely rethink how people interact with such devices, that for example, could be positioned anywhere in space compared to the user. Additional degrees of freedom, not only complexify our interaction models but also highlight some of their limitations. The difficulties in creating Unbound interfaces are not merely a matter of adapting findings from ground robotics or from the autonomous vehicle literature because there are fundamental gaps in our understanding of the scientific and technological knowledge required to develop such systems. For instance, current interfaces are primarily conditional to their context of use and lack ecological validity for machines that will be deployed beyond Earth surface, such as in space. We furthermore need novel methodologies and metrics to define successful interactions. In summary, while interaction techniques have been developed to support on Earth surface HMIs, it is not clear how current technologies and methodologies will support Unbound interactions.

3 Existing Unbound HMIs

Prior work researching interfaces where the machine is Unbound are primarily found in the Human-Drone Interaction (HDI) literature. In collocated HDI, many interaction techniques have been researched. Input from the user to the drone can use a plethora of modalities, from voice [46] and gestures [9, 43] to gaze [34] and touch [1, 38] (see full surveys [57, 26]). Diverse modalities have been proposed to output information from a drone to a user – in collocated settings. One of the prominent modalities is visual, where for instance: LEDs have been used to convey a drone's intent [55, 21]; a screen to convey information [50] or even the drone's emotional state [25]; a projector to display a UI [5, 10]; a beam of light to indicate a point of interest [36]; and the drone's movement to convey intent and affect [51, 54, 11] or indicate the way [12]. Another modality is audio, where Lieser et al. [37] proposed the use of vocalics, such as to attract a person's attention.

The research on interfaces for which the human is Unbound is, however in its infancy. Prior works have explored HMIs between autonomous underwater robots and diver(s), but primarily focusing on technical solutions (e.g., computer vision, algorithm, and machine learning contributions) to make the interaction work [14, 15, 32]. We further find discussions around underwater humanoid robot interacting with a diver [35] or as proxy for interaction between a diver and a remote operator [4]. However, the work did not focus on the interfaces themselves and whether they were suitable in such environment. We further find devices

such as in-cabin flying robots aboard the space station [17] (e.g., CIMON [2], Astrobee [7], BIT [39]), which have been designed with multi-modal input and output capabilities to communicate directly or indirectly with the astronauts' crew (e.g., to convey state and intentions). Some of the challenges for HRI in space have already been identified [20, 44, 45], including discussions on the challenges of using input devices that are Unbound in micro-gravity environments [6]. Furthermore, recent work proposed adapted technical solutions to the use of eXtended Reality (XR) in space [49], highlighting limitations of current hardware development to their use in space. All these exemplify the emergence of the field and the interest for interacting in Unbound contexts.

4 Need for Theoretical Modeling

We here propose that beyond technical solutions, theoretical models are needed to support the design and evaluation of unbound interfaces. One theoretical framing that could be adopted is to use the concept of joint cognitive systems, which focuses on the cognitive aspect of the human-machine interaction. The initial term was Cognitive Systems Engineering (CSE) [27], with its central tenet being that a human-machine-system needs to be conceived, designed, analyzed, and evaluated in terms of a cognitive system. The configuration or organization of human and machine components is a critical determinant of the outcome or output of the system as a whole. One of CSE fundamentals is to explore how humans and devices can be described as joint cognitive systems (JCS), and how this extends the scope from the focus on the interaction between human and machine to how humans and technology effectively can work together [28]. JCS, however, does not focus on the interaction between human and machine, but instead focuses on the external function (i.e., the result of their activity). One key element to such theoretical model will be to establish what "joint cognition" is between devices and users with a focus not only on human factors [29] but also on traditional HCI. Such factors could then include perception, affordance, coordination, trust, and resilience in support of establishing a joint cognitive system. Empirical research will be primordial in establishing theoretical models, and as such, we envision running simulations, as well as user studies in real (e.g., underwater, analog missions) or simulated environments (e.g., parabolic flights). A next step will then be to provide design principles that take into account the varying applications of the rules of physics based on the environment of both machine and human.

5 Future Work and Conclusion

Much research is needed to fully provide one or several theoretical models that can support unbound interactions, such as interactions happening between human and machine in space. It will require both theory and empirical research to identify the various parameters, as well as a complete re-thinking of interactions beyond traditional laws of physics within Earth surface constraints. This work presents a thought-provoking position paper conceptualizing various types of interfaces and interactions happening beyond the Earth surface. It attempts to identify existing literature that falls within this concept and proposes potential direction for modeling unbound interactions.

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CASIMAR, a Collaborative BVSR Project

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Abstract

CASIMAR is a pioneering collaboration project within the Bundesverband studentischer Raumfahrt e.V. (BVSR), uniting student groups across Germany in designing, developing and testing a modular lunar rover and specialized EVA (extravehicular activity) tools for human-robot interaction experiments at the LUNA Analog Facility in Cologne, Germany. This student-driven initiative aims to establish a lasting framework for integrating projects of BVSR into the professional lunar exploration research environments. The rover development focuses on three mission scenarios: EVA support, search & rescue, and stand-alone operations, all focused on improving human-robot interaction for astronaut safety and efficiency. In parallel, students develop EVA tools which are essential for hands-on experience and also will be complementary to the rover's proposed capabilities. The tools also enable early testing campaigns within the LUNA Analog Facility before the rover's completion. To enhance design, training, and operational planning, CASIMAR will integrate a virtual reality (VR) environment that will serve as a digital twin of the rover and lunar setting, supporting interactive simulations, early-stage validation, and astronaut training. CASIMAR will not only contribute innovative technological solutions but also foster interdisciplinary collaboration and practical experience of future aerospace professionals.

2012 ACM Subject Classification Human-centered computing → Human computer interaction (HCI); Hardware

Keywords and phrases CASIMAR, BVSR, LUNA Analog Facility, rover, EVA, tools, students, collaboration, virtual reality, VR, digital twin, HRI, HCI

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1 Introduction

1.1 What is CASIMAR?

CASIMAR is the first hands-on development project, in which student groups from across Germany collaborate under the central management of BVSR. Its main objective is the development of a lunar rover and specialised EVA (Extravehicular Activity) tools for operations in the LUNA Analog Facility in Cologne, Germany. The project strives to provide students from different universities across Germany access to LUNA in ways that would otherwise be difficult to achieve for any independent student group. Most development aspects will focus on human-robot interaction (HRI), in line with the authors understanding of LUNA as a facility with a strong focus on astronautic aspects of lunar exploration.

Eight different student societies are currently collaborating in the project. The overall goal is to provide students with access to the LUNA facility and create heritage for using the facility for educational purposes. While parts of the CASIMAR team are focusing on designing and building a rover with a major focus on HRI, other parts of the team are focusing on the development of EVA tools and in situ resource utilization (ISRU) experiments. The overall idea is to integrate those two domains of the project into a joint experiment campaign down the line, to be executed in the LUNA Analog Facility by the students themselves.

This paper shall present an overview of the project, which is currently in the early stages of requirement definition. The authors submit this paper to foster discussion in the CHI/HRI community and wish to receive feedback on the current project approach from the community.

1.2 Bundesverband studentischer Raumfahrt e.V.

The BVSR serves as the umbrella organization for fourteen German and two Austrian student groups actively engaged in hands-on space-related projects. Founded in 2022, BVSR represents and supports these groups on the national and international stage. In total, BVSR supports over one thousand students in aerospace and aerospace-related fields of study. [1]

1.3 Organisational Structure

The CASIMAR Project is led by two senior students with prior project and group management experience on behalf of BVSR. Any member of any student group under the BVSR umbrella can participate in CASIMAR by expressing their interest in the project. If any particular student group is not already participating and is not represented in CASIMAR, a representative is chosen by the group to coordinate the activities of that group. This representative then reports to the CASIMAR management on behalf of that student group, but is also responsible for recruiting members for their team at their respective university. This structure is visualized in figure 1.

Each student group takes over one or multiple tasks, takes care of a specific subsystem of the planned rover, or an EVA tool. Their contribution to the overall CASIMAR project is being integrated in coordination with the CASIMAR management and the group of representatives. This hierarchy is not necessarily strictly enforced in all communication. Instead, direct communication within and across groups between all students participating in CASIMAR is actively encouraged to foster inter-group contacts and cooperation – while keeping the project management and group representatives informed of any progress and especially newly discovered issues. The current participating groups of CASIMAR are visualized in figure 2.

In addition, the CASIMAR management is responsible for the project's communication with ESA and DLR, and especially the personnel of the LUNA Analog Facility and ensures that any requirements or constraints – technical as well as organisational – set by ESA or DLR are being followed within the project.

Communication between multiple university locations is being established using modern video conference systems and instant messaging systems, but it is augmented by in-person meetings and workshops hosted by at the universities of the groups participating in CASIMAR.

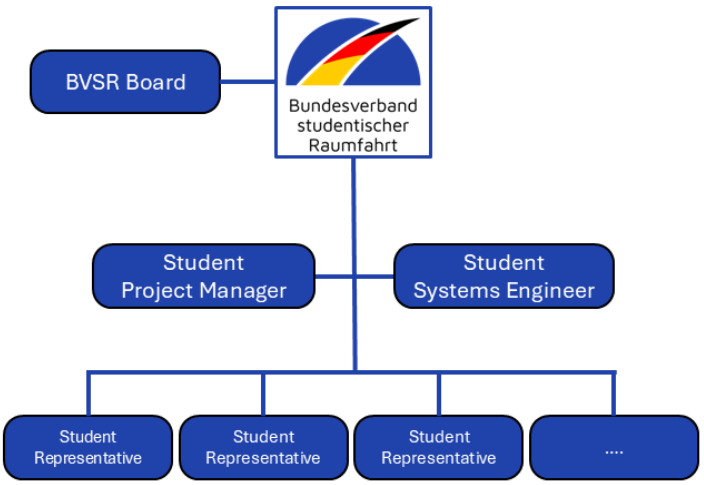

Figure 1 Schematic organigram of the CASIMAR project.

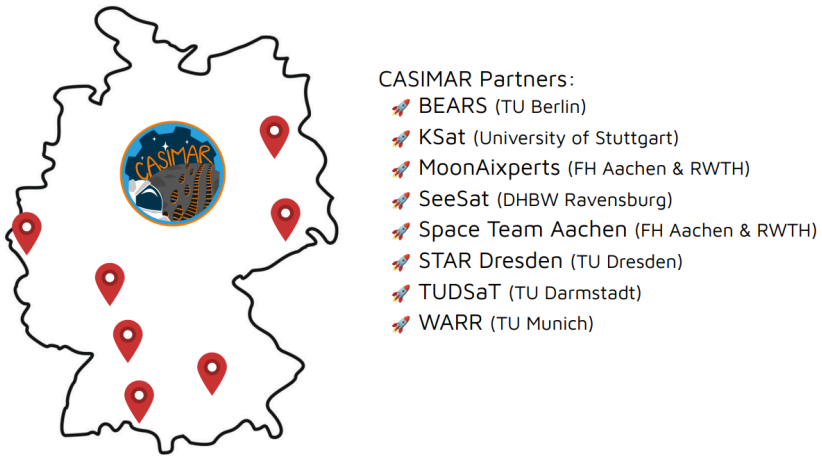

Figure 2 Locations and list of the groups currently participating in the CASIMAR project.

1.4 LUNA Analog Facility

The LUNA Analog Facility has been developed in cooperation between the German Aerospace Center (DLR) and the European Space Agency (ESA) in Cologne, Germany, to provide a sophisticated facility for testing and validating technology for lunar exploration. To allow

in-depth experiments and studies, LUNA offers several systems and capabilities for simulating the lunar environment, specifically the moons polar regions. At this time, a 33 m-by-20 m area filled with EAC-1A regolith simulant [2], seismic sensors, an adjustable lunar sun simulator, as well as several live-surveillance and live-communication systems (Monitoring and Control System, MCS-L) are available. The regolith bed also includes a deep-floor area with a depth of 3m that features underground structures such as an artificial lava tube at the bottom. Experiment data is collected by the facility and can be provided to a customer after a campaign. Integration for live interfacing, communication and control from ESA, MUSC or GSOC control centres is also possible. Future upgrades, in order of the current schedule, include the updated Candelabra Sun Simulator (Q4/2025), Extended Reality Motion Capture (Q4/2025), the Moon Zeppelin Ramp (Q1/2026), and the Puppeteer Gravity Offload System (Q3/2026). [5]

2 CASIMAR Project

2.1 Lunar Rover Platform

The project's core concept revolves around the development of a modular rover platform for use in the LUNA Analog Facility, with several groups responsible for creating the main platform. Additional groups would contribute instruments, payloads, software, and other essential components, fostering intergroup collaboration.

To the knowledge of the authors, there is currently no rover-development focused primarily on human-robot interaction in an extraterrestrial context. The obvious exceptions are past and present developments of astronaut mobility rovers, like the Apollo Lunar Roving Vehicle, but these differ significantly from the scope of the proposed CASIMAR rover. The main focus of CASIMAR will be HRI in an astronautic lunar exploration context, with the goal of presenting a testing environment for rover-based HRI and providing tangible research into this field. In other words; How can an astronaut interact with an independent rover companion during EVAs and beyond.

As a student project, it shall provide training opportunities for future engineers, researchers, and managers of astronautic missions.

The development of the rover is currently in the early stages of requirement-based engineering. Three general mission types were devised to cover broad aspects of an astronaut supporting rover: EVA support, search & rescue, and stand-alone operation, which are introduced in the following paragraphs. These different mission types represent different magnitudes of HRI the rover platform shall be designed for; cooperation with astronauts and support during their activities, helping an injured or potentially even incapacitated astronaut, and independent operation without personnel in the vicinity of the rover respectively. The missions are conceptualised in such a way that the finished platform can be tested in the LUNA Analog Facility. The extent to which the rover will be able to handle the different aspects of the presented missions is subject of the upcoming detailed rover development.

At first, the rover shall primarily be developed as a remotely operated vehicle, preferably using the remote control capabilities provided by the LUNA Analog Facility. The rover shall enable the implementation of different degrees of autonomy to enable research into the field of HRI with autonomous machines specifically.

EVA Support

The primary design driver of the CASIMAR rover development shall be the support of an astronaut or multiple astronauts during their EVA activities. To facilitate this, the mission was not designed with tasks specifically for the rover to accomplish, but instead with general or abstract tasks for the astronauts to complete. The rover shall then be designed to support the astronaut or astronauts during these tasks.

Examples of these tasks are:

- Taking surface samples in designated locations,
- Deploying scientific equipment on the surface and/or recover such equipment, or
- Conducting maintenance activities on surface-equipment (habitation infrastructure, landers, etc.).

Some example capabilities the rover could be designed for in this supportive role are:

- Transport of scientific equipment and tools,
- Guiding an astronaut on a safe path,
- Providing illumination during transit and in the target region during a task,
- Providing external camera view to observe the astronaut during a task,
- Transporting samples for the astronaut, or
- Providing a relatively clean work surface for the astronaut during tasks ("workbench" or potentially a glove box).

Search & Rescue

Even with every feasible precaution and safety feature, lunar exploration will still be a risky endeavour. In case an astronaut is injured or even incapacitated during an EVA, the rover shall be able to provide support. This support is grouped into several different levels of complexity with example tasks a rover could be designed for at each level:

- Search; The rover shall be able to locate an astronaut on the surface and distinguish them from the surroundings, even in adverse lighting conditions (up to total darkness) and with the astronaut lying on the ground.
- Beacon; After spotting the astronaut, the rover shall act as a beacon for other astronauts to find the downed colleague immediately.
- First Aid; Once located, the rover shall provide "first aid" to the astronaut. This could mean extending the usable life support duration by coupling a "first aid" payload to the astronaut or other forms of first aid feasible within the constraint of an EVA suit.
- Rescue; If possible, the rover should guide the astronaut back to safety or even transport an incapacitated human.

Stand–alone Operation

An astronaut will not be able to work 24 hours per day, 7 days per week but instead will need breaks and downtime. A lunar support rover should use this downtime to accomplish additional tasks on the surface independent from the astronauts in order to increase the utility of the allocated mass, which has to be transported to the lunar surface in the first place. The following example tasks could be archived by a rover without an astronaut, if considered during the design of the rover:

- Check on equipment placed on the surface previously,
- Scout a path for a future EVA (detailed Mapping and hazard identification),
- Deploy specific scientific payloads, or
- Retrieve specific scientific payloads and surface samples.

2.2 EVA Tools for Lunar Exploration

The basic challenge in keeping a voluntary student project active is to motivate students to participate over the entire course of the project. As CASIMAR is self-organised by students under the BVSR-umbrella, it is not part of any university curriculum and has therefore no external motivator. With the rover as a long term development goal on the order of multiple years, this continuous motivating of students is achieved by tangible development tasks that new members can accomplish in a relatively short time frame with little prior experience.

For CASIMAR, the development of specialised EVA tools was chosen as such a short term development task, in parallel to the rover. This enables students to get hands-on experience with a variety of tasks that require them to think about, e.g., safety requirements for interaction with astronauts, the available features of the LUNA Analog Facility, and ultimately the HRI elements by thinking about how those tools can complement the rover later on.

Furthermore, the development of EVA tools allows for multiple preliminary campaigns in the LUNA Analog Facility before the rover development is completed, which enables the CASIMAR project to establish heritage for future campaigns. This way campaign logistics can receive multiple trial runs and the overall interaction between the LUNA Analog Facility team and the CASIMAR project and BVSR in general can be established. At this time, four different student societies – BEARS, KSat, MoonAixperts, and STAR Dresden – are working semi-independently on various EVA tools and ISRU experiments, of which some prototypes will be tested in an integrated setup in the LUNA Analog Facility in 2025. It is intended that this integrated test will be conducted in a fully simulated analogue spacewalk scenario with the HECC (Human Exploration Control Center) in Munich, Germany, involved in the planning and execution of the tests, providing remote operational capabilities to guide the analogue spacewalkers through the simulated EVA.

The tools for this first campaign are currently under development. They include a multi-tool, which can be used to pick up small rocks and hold a dust bag. Unique features of this tool are the integrated light source through an detachable light, which helps the astronaut see the surface in the previously described lighting environment, as well as the heavy use of compliant mechanisms to avoid the use of dust-sensitive bearings wherever possible.

In addition to the multi-tool, a small handheld regolith sieve will also undergo testing during the first experiment campaign. The main objective is to allow Astronauts to filter small regolith samples based on different grain sizes. The sieve's design is tailored to be used with bulky EVA suits, especially the gloves, and can be operated entirely without the need for any additional equipment. However, combining it with the multi-tool can be beneficial. The operating principle is based on centrifugal force, which pushes the collected regolith samples through a filter. The sieve also contains the complete sample to minimize dust generation to avoid inhibiting the astronauts visibility.

Apart from the hand tools, a previously developed vibration based regolith conveyor system shall be tested for its deployment ergonomics within the constraints of an EVA suit. [6]

2.3 Usage of VR Simulation

Accompanying the rover and EVA tool development will be the development of a virtual reality (VR)-environment, serving an array of purposes throughout the life cycle of the CASIMAR project. The proposed VR-environment, similar to the rover, will be subject to

concurrent engineering processes and gain complexity along with the rover design, serving as a digital twin for initially designing, later training, and finally possibly operating the system. The more immediate advantage of the VR-environment shall be the evaluation of the rovers design by displaying models of the rover and its constituent parts in the environment it is later deployed in, leveraging benefits of experiencing the rover to scale in conditions that the rover and corresponding EVA astronaut are expected to experience. An example for these conditions are the challenging lighting conditions of the lunar south pole as well as lunar gravity as has been explored for the Argonaut lander, formally known as EL3, in the works of Nilsson et al. [4]. This will provide insightful feedback at an early stage that common design review processes may only allow post assembly with the rover, or in the case of environment interaction, post utilization.

Initially limited to review of the physical elements but also later given a finalized and frozen hardware design, it is intended to facilitate software tests with an emulation of the rovers operating system in the VR environment providing early insights into how it interacts with a lunar environment as well as providing a testing environment for interactions with astronauts without risks of injuries due to unexpected behaviour of robotic components.

At the end of the design phase the VR-environment should contain a digital twin, with the virtual rover mimicking the appearance and behaviour of the physical counterpart. It is further envisioned to utilize this digital twin as a foundation for training elementary rover interactions for the accompanying astronauts, as well as emulating entire multi-stage missions as may be expected during actual lunar expeditions, to reduce risk and provide familiarity with the procedures ahead of time, with the perspective of applying game-based learning similar to the JIVE platform [3]. These trainings may reduce the time to learn the rover interactions drastically and may be done in the absence of the rover, which there will potentially only be one manufactured prototype of. Finally experimenting with facilitating the actual commanding of the rover using VR in our environment is proposed, by then only requiring synchronization between the physical and virtual rover, including the changing environment, and commanding capabilities of the VR-application as a new and alternative way to handle the control of the rover. For the commanding abilities, various input devices will be considered and evaluated on their intuitiveness and coverage of rover controls, to then assess their effectiveness for physical and digital rover control. This has only been identified as a subject requiring further research and will be pursued once the design of the rover and the corresponding controls of it and its potential payloads have been consolidated.

3 Conclusion and Outlook

The CASIMAR project represents an ambitious step forward in student-led lunar exploration research, uniting multiple student groups under the BVSR to design and develop a modular rover and specialized EVA tools. By leveraging the unique capabilities of the LUNA Analog Facility in Cologne, Germany CASIMAR aims to establish the foundation for future interdisciplinary collaboration in the field of human-robot interaction (HRI) and lunar mission support technologies at a student level.

The participants have successfully established organisational structures to enable development of a rover capable of EVA support, search & rescue, and stand-alone operations. In parallel, the development of EVA tools will provide a valuable hands-on experience for students while enabling early testing campaigns that will enhance astronaut capabilities in lunar analogue environments. Furthermore, the integration of a virtual reality (VR) simulation environment as a digital twin for design validation, astronaut training, and operational

planning will add another layer of innovation to the project. The VR environment will facilitate iterative design processes and risk-free testing, thereby improving the rover's overall efficiency and usability.

Looking ahead, CASIMAR aims to transition from its current conceptual and requirement definition phase into full-scale development, implementation and testing. Key future milestones include:

- Completion of requirement definition of the rover based on the proposed mission types.
- Conducting full-scale simulated analogue spacewalks of students in the LUNA Analog Facility testing student-developed tools, refining their design and operational effectiveness with support from ESA/DLR.
- Implementing the VR simulation environment to simulate real-time interaction with the rover, supporting astronaut training and remote operations.
- Establishing strong ties with space agencies, research institutions, and industry partners to secure funding and technical support for long-term sustainability.
- Encouraging more student groups to participate in CASIMAR, thereby expanding the project's reach and fostering continuous knowledge transfer.

CASIMAR will not only contribute to technological advancements in lunar exploration but will also help train the next generation of aerospace engineers, researchers, and managers. By maintaining its focus on interdisciplinary and interregional collaboration, modular system development, and immersive simulation, CASIMAR can provide great benefits in the field of lunar exploration. The coming years will be crucial in transforming the project's ambitious vision into tangible contributions for space research and astronautic missions.

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Design as an Astronaut: An XR/VR Experience of the Argonaut Habitat Unit

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Abstract

This research explores the conceptual design of a lunar habitat integrated with the Argonaut lander, an autonomous lunar landing vehicle currently under development by an international consortium led by the European Space Agency (ESA). As Europe's first lunar lander, Argonaut was conceived to provide ESA and relevant European stakeholders with independent access to the Moon. Although the lander is primarily designed to transport various types of cargo to the lunar surface, this study proposes its adaptation as a platform for future human habitation: the Argonaut Habitat Unit. The project is the result of an international collaboration between ESA, the MIT Media Lab, and Politecnico di Milano. Drawing on a wide range of methodological approaches, this paper reflects on key aspects of the concept, including its synergy with the existing Argonaut project, algorithmic modeling of a lunar habitat, consideration of technical requirements, and interior design development. The project addresses the spatial, material, and environmental constraints of lunar habitation through a combination of three-dimensional modeling software, computational design tools, and virtual reality (VR) development environments. The integration of VR offers an immersive understanding of the proposed habitat, enabling a first-hand experience of its spatial qualities. This approach supports both the evaluation and refinement of the design, enhancing its livability and practical feasibility.

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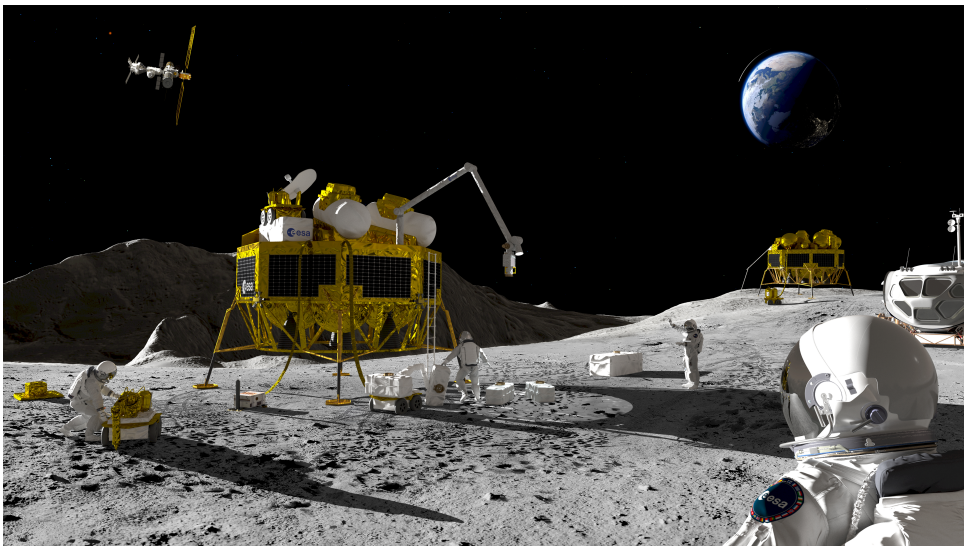

Figure 1 Rendering of the Argonaut lander (source: [7]).

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1 Introduction

The name "Argonaut" continues the tradition of naming lunar missions after characters from Greek mythology, following in the footsteps of the Apollo and Artemis programs. The Argonauts were the brave sailors who ventured with Jason on his legendary quest to retrieve the golden fleece. In this tradition, each forthcoming mission of the Argonaut lunar landing vehicle (Fig. 1) will carry the name of a different mythical Argonaut, celebrating their adventurous spirit. Argonaut has been designed to ensure reliable transport of cargo supplies and other payloads to the lunar surface. Although still in the design phase, current concepts envision the lader to be approximately 2.8 meters tall, with an octagonal cargo deck of approximately 14 m^2 on its upper surface [15]. Once operational, the Argonaut is expected to serve as a cornerstone of Europe's roadmap for sustainable human lunar exploration [8, 2]. The initial launch of the Argonaut lander is planned for approximately 2029, pending further mission development [19]. Each Argonaut mission will follow a carefully calculated 5-day transfer orbit to optimize energy usage [13]. Upon descent and landing, the Argonaut will serve as a platform to facilitate a range of activities, such as science and exploration, technology demonstration, power generation and distribution, and in situ resource utilization [7].

This paper proposes to further expand the Argonaut's scope of use by repurposing its landing body as the foundation for a habitable lunar module. The resulting *Argonaut Habitat Unit (AHU)* is designed to support a crew of two astronauts for a baseline mission duration of 14 days, with the flexibility to extend up to 4 weeks.



Figure 2 External view of the AHU in the VR environment (source: authors).

Although the exact landing sites of upcoming Argonaut missions have not yet been determined, the objective is to develop a system that can be deployed anywhere on the Moon, providing a versatile platform for short-term – and potentially medium to long duration missions with additional radiation shielding through In Situ Resources Utilization (ISRU), as current protection is limited to approximately four weeks – lunar exploration and habitation. [7].

2 The Argonaut Habitat Unit

This section presents the proposed integration between the Argonaut lander and the AHU, detailing how the habitable module has been conceived and designed through the integration of computational design methods and XR/VR tools within the overall development process. (Fig. 2).

2.1 Computational Design Strategy

The habitat design was developed by combining three-dimensional direct modeling with computational design tools [25]. Grasshopper, a visual algorithm editor integrated with Rhinoceros 3D, was used – along with various plugins – to carry out the form-finding process and structural analysis of the inflatable shell. Rhinoceros 3D was also employed to model the interior spaces of the habitat [23].

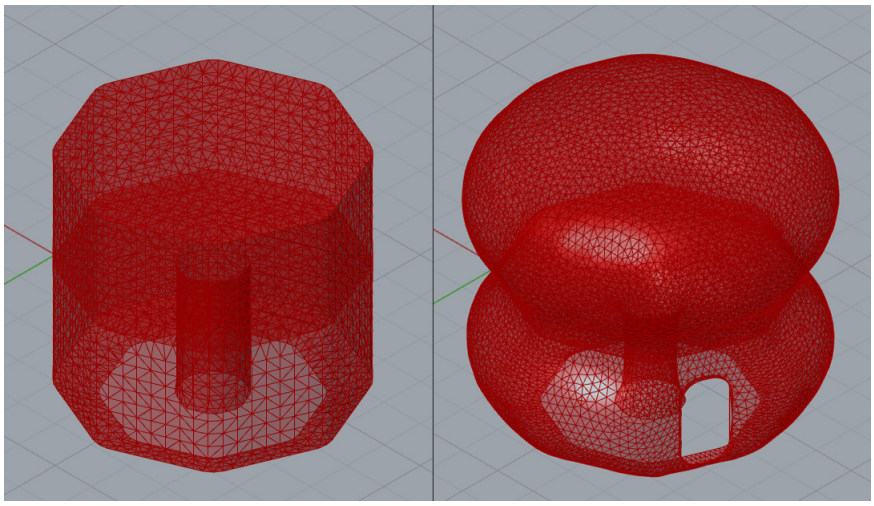

Figure 3 Mesh before and after inflation (source: authors).

Starting from the shape of the Argonaut lander, which provides an octagonal base for the habitat, the initial internal layout was conceived by adapting the shape and distribution of the rooms to fit within the octagon. Due to the limited dimensions of the Argonaut base, which is approximately 4,5 meters in diameter, the design concept includes two levels to accommodate all the functions required to support two astronauts during a four-week mission. This initial design phase allowed for the definition of rough spatial volumes, including a central circulation space connecting the two levels. This information served as the basis for the form-finding process.

Thanks to the effective interoperability between Rhinoceros and Grasshopper, data from the 3D model was imported into the Grasshopper scripting environment. This included the perimeter of the Argonaut base, the surfaces representing the room volumes, the airlock position and shape, the baseline of the central connecting element, and the perimeter of the first floor. The perimeter of the base, the perimeters of the floor and ceiling of the first level, and the points of the airlock were used to define anchor points for the form-finding analysis, allowing the inflated shell to follow the shape of the previously defined volume. The surface representing the room's volume served as a base for creating the mesh that would later be inflated.

Once the data was collected and organized, the form-finding process began. This was carried out using Kangaroo Physics, a live physics engine for interactive simulation, form-finding, optimization, and constraint solving, integrated within the Grasshopper environment. Additionally, Weaverbird, a plugin for mesh manipulation, was used to refine the geometry. (Fig. 3).

2.2 Structural analysis

After the form-finding process of the AHU, the mesh was structurally evaluated through finite element method (FEM) analysis using Karamba 3D. Kevlar was considered the primary structural membrane for the outer shell. The resulting homogeneous stress distribution confirmed the feasibility of maintaining internal pressurization at 1 atmosphere under lunar conditions, accounting for the Moon's reduced gravity (1/6 g), appropriate safety factors, and fixed geometric constraints such as the airlock and the structural perimeter. The analysis

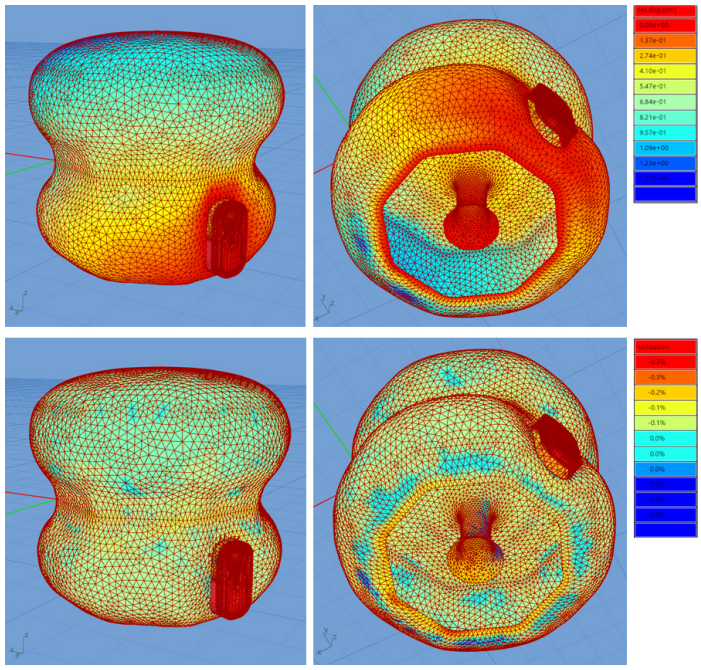

Figure 4 Structural analysis of the AHU (source: authors).

was based on applied loads corresponding to internal pressurization and lunar gravity, with a Kevlar layer thickness of about 5 mm. The inflation and structural evaluation were conducted using Kangaroo Physics and Karamba 3D. Ultimately, the shell structure was designed with a total thickness of 30 cm to incorporate radiation shielding layers, envisioned to be achieved using a mycelium-based infill material that could potentially be grown directly in situ. (Fig. 4).

2.3 Materials

The material selection for this design was crucial to meet the constraints of the mission. The Argonaut lander has a payload capacity of 1,800 kg [13]; therefore, the materials chosen for both the external shell and interior elements were required to be extremely lightweight to facilitate integration with the lander.

The lunar environment presents challenges that can be addressed through an informed material selection process. The Moon's surface is exposed to high levels of radiation, including GCR (Galactic Cosmic Rays) and SPE (Solar Particle Events) [9]. Consequently, the design must incorporate materials capable of reducing radiation exposure within the habitat, ensuring the safety of astronauts.

The main materials selected for the inflatable shell were mycelium and a lightweight multilayer membrane. The membrane forms both the outer and inner layers of the shell, with the mycelium growing in between. The membrane is composed of multiple materials that address the various hazards of the lunar environment as well as structural requirements. It protects against micrometeoroid impacts and extreme temperature fluctuations, provides structural stability, and ensures gas impermeability. The material composition of the membrane proposed for the AHU builds on previous studies of inflatable space habitats for the Moon and Mars, which explored novel combinations of materials to create lightweight and resilient inflatable structures. [20] [21].

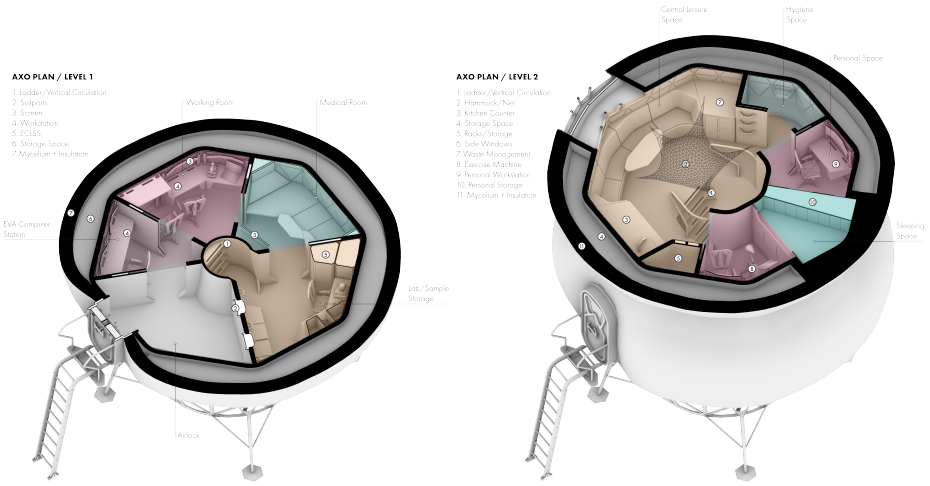

Figure 5 Axonometric plan views of the Argonaut Habitat (source: authors).

This membrane has been integrated with mycelium which was selected due to its low weight, favorable strength-to-weight ratio, and its potential ability to shield against radiation [22]. Together, these materials provide a lightweight, strong, and radiation-resistant structure, capable of sustaining human life for the planned mission duration.

The interior design followed the same lightweight principle to comply with the Argonaut's payload requirements. Carbon fiber was selected for all interior elements – walls, ceilings, doors, and furniture due to its lightweight and versatility [5].

2.4 Interior design

This proposal introduces an inflatable module integrated with the Argonaut lander, forming a two-level lunar habitat. The design addresses both the operational and residential needs of astronauts during lunar missions. Its spatially efficient and modular layout ensures both functionality and comfort.[1].

The interior design of the envisioned AHU was structured along two separate levels (Fig. 5), which are both designed considering existing research and contemporary building practices in space architecture. Its purpose was to optimize for the physical, functional, and psychological requirements of the astronauts during isolated and confined missions in extreme environments.

Level 1 (Fig. 5) covers research, treatment, and operational functions. This level of the inflatable habitat is organized to address all operational needs on a day-to-day basis [1]. The spatial program sequence begins with an airlock designed for extravehicular activity (EVA) preparations, occupying a total area of 6.3 m^2, followed by a 2.9 m^2 EVA control room. The route continues into a 4.4 m^2 working zone, serving as a flexible workspace for ongoing technical and logistical tasks [1]. Next to the workspace, there is a medical room which covers an area of 4.4 m^2; this can be used for in-situ health monitoring and minor treatments and it is equipped with communication systems to ensure direct contact between the crew

members and doctors on Earth. Adjacent to the medical space, there is a 6.0 m² laboratory space that contains a suit port access, life support systems, and a scientific research corner with sample storage and scientific instrumentation.

At the center of this level, a mushroom-shaped vertical circulation shaft connects Level 1 and Level 2. Its semi-transparent enclosure and distinctive form serve a dual purpose: facilitating movement between levels and functioning as a daylight shaft, supporting the regulation of astronauts' circadian rhythms through integrated LED lighting.

Level 2 (Fig. 5) focuses on living and psychological well-being. This level is designed for comfort, recovery, and socialization purposes. At its center there is an 11.6 m² dining and recreation zone, designed as a leisure space in which astronauts can eat, relax, and socialize. At the top center of this space, there is a net that can be hung like a hammock thus increasing the playfulness of the space while providing an alternative relaxing area. Two corridors of this space reach personal and private spaces (each 2.9 m²) that offer a place to sleep, exercise, work, or be alone. Although compact, each private quarter meets contemporary habitat standards, with a particular emphasis on supporting mental health in confined environments. These small rooms are vital to the daily routine of the occupant's life, with efficiency, sanitation, and privacy provided. On one side of the corridor, there is a 1.5 m² hygiene space with a shared toilet, and on the other side, there is a flexible storage and plant growing space with modular racks.

In order to optimize the inflated form, the intermediate space between the organic outer shell and the flat interior walls has been utilized for water storage, modular equipment storage, support systems for the outer shell, and waste management. In this way, the volumes required for interior functions have been relocated into this in-between volume.

Design decisions and spatial distribution were guided by integrated references and human factors, drawing from internal layout models of the lunar habitat project developed by Burke, Howard, and Kessler [1], as well as the Moon Village concept designed by ESA, SOM, and MIT [11], which offers valuable insights into crew operations and behavioral health. The sight of the lunar surface is expected to be a significant consideration in sustaining astronauts' mental health over long periods of isolation. Inspiration is also drawn from terrestrial projects like the Copenhagen Metro Station by GXN [10], where daylight, clarity of space, and calm material palettes are strategically used to reduce psychological stress in underground environments.

Lighting strategy

The shapes generated in the habitat were intended to fulfill both physiological and psychological needs. A strategically placed window in the kitchen and relaxation area offers astronauts a view of the lunar surface and, when possible, the Earthrise from the South Pole – an iconic visual that can evoke the Overview Effect and strengthen emotional connection to Earth. Additionally, a central skylight in the ceiling of the second floor provides another viewpoint of the external environment, enhancing spatial orientation and supporting psychological well-being. (Fig. 6).

Due to the limited availability of natural daylight during lunar missions, artificial lighting becomes essential – especially in replicating circadian rhythms in a diffuse and seamless way, such as through ambient lighting. Adjustable LED systems are integrated within the triangular textile wall panels, allowing modulation of brightness and color temperature at specific times of day. This setup simulates Earth's natural light cycles, helping astronauts maintain healthy sleep patterns and emotional stability. Beyond that, the lighting can be personalized – with calming blue tones to enhance focus and warmer hues to promote

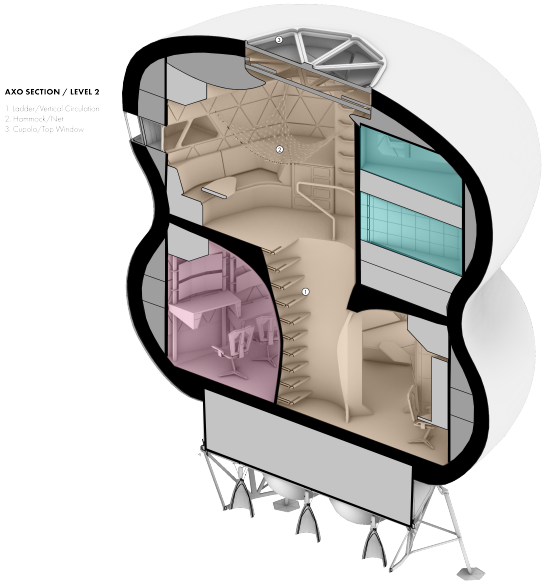

Figure 6 Perspective section of the Argonaut Habitat (source: authors).

relaxation – enabling astronauts to adapt the atmosphere to suit their tasks or moods. These subtle environmental shifts can make a crucial positive difference, particularly during long-duration missions in extreme conditions.[24].

3 Immersive and multi-sensory co-design experiences and environments

3.1 VR and XR

The integration of computational design into the project enabled its extension into XR environments, thanks to an algorithmic-based approach in Grasshopper. This virtual environment was designed to explore and evaluate key aspects of habitability, placing a strong emphasis on human factors and ergonomics. The use of additional design tools, such as Cinema 4D and Substance Painter (Fig. 7, 8, 9), allowed for a relatively fast and efficient translation of the complete design concept into high-fidelity interactive VR simulations. Such simulations have a long-standing track record of supporting visualization and collaborative assessments of human–environment interactions and building performance in both architectural research and practice [12].

The flexibility, and affordability of these simulations lend themselves particularly well to the space exploration domain, where physical prototype construction is oftentimes slow and resource-intensive, and replicating the extreme conditions of space habitation can prove hazardous or impractical in real-world settings. Conversely, the use of VR enables efficient interactive visualization of prospective design solutions and their operation under key lunar environmental conditions, such as hypogravity and unique illumination, providing a means for early-stage feasibility studies. Indeed, ESA's initial VR-based evaluations of the Argonaut lander have already produced meaningful insights, including optimal placement strategies for solar panels and safety railings [15].

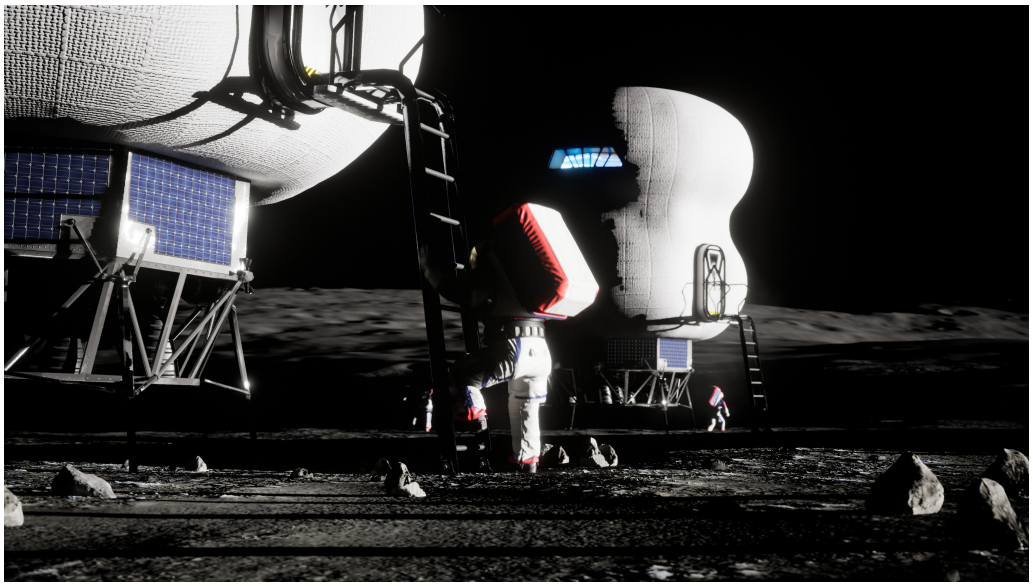

Figure 7 External view of the VR environment (source: authors).

To situate our simulated Argonaut Habitat Unit within a realistic operational context, we generated an authentic lunar landscape using topographic data from NASA's Lunar Reconnaissance Orbiter [4]. Specifically, we recreated the Shackleton Crater region near the Moon's south pole - the likely destination of forthcoming crewed lunar missions. This terrain, along with the 3D model of the habitat unit, was subsequently imported into Unreal Engine 5, allowing for accurate real-time simulation of lunar illumination conditions and gravity. Finally, to enable users to fully immerse themselves in this virtual environment, we used the Varjo XR-3 headset.

Initial studies based around this virtual environment were conducted at ESA's Extended Reality Laboratory, located at the European Astronaut Centre in Cologne, Germany. Being the home to a wide range of uniquely qualified experts, including astronauts, aerospace engineers and lunar scientists, the centre provided us with ample opportunities to assess our design and collect constructive feedback.

Using the VR simulation, relevant experts were able to navigate the habitat in first person, exploring spatial configurations and evaluating the usability of key components under simulated lunar conditions. Our primary objective was to support expert assessment of the interior design and furniture layout, as well as to assess human factors, usability, and overall operational efficiency. The feedback was especially valuable in evaluating the feasibility of proposed laboratory activities, ergonomic aspects, and the arrangement of sleeping quarters and exercise areas, which included integrated physical training equipment. The airlock and its spatial configuration, including the central ladder connecting to the second level, were also carefully reviewed.

The immersive experience enabled the collection of real-time feedback on key aspects of the habitat, including movement flows, visibility, instrument accessibility, and perceived comfort within confined spaces. Insights gathered through these evaluations informed iterative design refinements, helping to ensure that the layout meets technical requirements while also supporting both cognitive and physical well-being.



Figure 8 Internal view of the kitchen (source: authors).



Figure 9 Internal view of the workstation (source: authors).

Moreover, these VR and XR simulations facilitated interdisciplinary dialogue between designers, engineers, and human factors specialists, reinforcing the importance of a user-centered approach in space architecture. By simulating realistic scenarios – such as emergency egress, scientific operations, or routine daily activities – the system provided valuable insights into the operational viability of the habitat prior to any physical prototyping. Most importantly, it enabled the direct incorporation expertise of astronauts and other experts into the design process, transforming it into a truly collaborative, multidisciplinary co-design experience.

3.2 Soundtrack

The soundtrack for these animations came from two autonomously-running, complex patches on a large, custom-made modular synthesizer. The first patch generated the soundscape to match the "outdoor" lunar environment, while a subsequent patch was designed to generate the soundscape for the sequences inside the habitat. These patch compositions, along with most of the synthesizer hardware, were designed by co-author Joe Paradiso, who has been evolving this synthesizer system and composing with it for a half-century [18, 17, 16]. The "programs" that generated these soundscapes were essentially determined by the patched modules and their settings. These patches each used many hundreds of cables (see Fig. 10 for a view of the habitat interior soundscape patch in action), that connected well over a hundred modules and effects pedals modified to allow voltage control. These soundscapes were each generated in real time and the audio was directly recorded – what you hear is what the patches do live. They are very complex, and involve sonic layers that trigger and change. The "scheduler" here is essentially patched logic driven by several independent (and randomized) clocks - depending on how the clocks and counters driven by them align, different audio events are triggered in different ways, hence the patch never really repeats and keeps evolving. The audio snippets used in the video soundtrack were chosen from 3-hour contiguous recordings made from each of the patches.

Each of the two soundscapes were composed to support different atmospheres. The outdoor segment was meant to evoke the extreme feeling of celestial awe that one would get when physically on the lunar surface, produced mainly by dreamy pad-dominated textures, mellotron choirs, etc. These are supplemented by bursts of driving sequencer ostinatos (inspired by the 1970s Berlin-School music of Tangerine Dream [6], etc.), which convey a sense of motion and purpose. When one thinks of outdoor lunar operations, it is natural to want to add astronaut radio voices. Rather than use actual astronaut recordings or attempt to make them out of real voice samples (which could get repetitive), the "voice" sounds that come in occasionally are purely synthetic, generated by a phoneme module based on a Votrax voice synthesizer from the early 1980s [18]. This is driven by a pseudo-random generator with dynamically switching sequence lengths (giving the illusion of different phrases), all shifted up by a ring modulator running at periodically changing frequencies, with some distortion added here and there to yield a space "radio" dialog quality. While the "indoor" portion also attempts to maintain a sense of otherworldliness, it is perhaps more "utilitarian". It began with a background bed of occasionally triggered audio samples of mechanical clacks and droning/whirring motor sounds that the composer recorded back in the late 80s. The use of these samples was inspired by discussions among the authors of how infrastructure sounds can be prevalent in space habitats, together with how astronauts described the sonic environment in the cramped Lunar Module while on the Moon's surface [3]. Many other sonic events come and go, bringing this soundscape from a tonal/ambient environment into a more retro-avant "beepy" BBC-Radiophonic-style [14] landscape with an occasional grandiose pad sweeping in here and there.



Figure 10 The synthesizer patch generating the "Indoor" soundscape in action (source: Joseph Paradiso).

4 Conclusions

This paper investigates the potential of adapting the ESA Argonaut lander as the foundation for a human outpost on the Moon, referred to as the Argonaut Habitat Unit. Through a multidisciplinary approach that integrates architectural design, engineering, computational modeling, and immersive technologies, a habitat concept was developed to address the complex and interdependent requirements of a lunar environment. The computational design process enabled the simulation of structural inflation and its subsequent analysis, supporting the form-finding process and grounding it in real-world physics. XR and VR technologies provided an in-depth, immersive understanding of the design, enabling astronauts and ESA experts to engage directly with the proposed habitat in a simulated environment. This not only facilitates the validation of spatial solutions, but also opens opportunities for astronaut training, stakeholder engagement, and iterative development. The study demonstrates how multidisciplinary design strategies can enhance existing aerospace systems and contribute to the realization of sustainable human habitation on the Moon.

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A Postcard from Mars: Exploring Interplanetary Communications in Virtual Reality

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Abstract

In this paper we present an *Immersive Speculative Enactment* focused on the theme of interplanetary communications. These are a novel approach extending conventional Speculative Enactments to Virtual Reality. We created a narrative-based scenario in which participants played the role of human colonists on either Mars or the Moon, to explore a possible future in which interplanetary communication becomes a necessity. To enact this scenario, we created a VR interactive experience to elicit feedback on the idea of communicating across planets. Through an exploratory qualitative analysis of this immersive enactment, we found that while the future envisioned was seen as too distant to prompt realistic behaviour from all participants, the enactment helped us and the participants to reflect on the experience. We discuss these findings, drawing potential implications for the improvement of the feeling of "really being there" even in implausible situations and further contribute reflections on the role of ISEs in space-related scenarios.

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Keywords and phrases Immersive Speculative Enactments, Interplanetary Communications, Virtual Reality

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1 Introduction

In HCI, the concept of "Possible Futures" [19] has gained attention, the idea that a research artifact exists within a set of exact circumstances, that might deviate from the effective state it will be in, once deployed in its context of use. The more distant this future is, the greater the "cone of possibilities".

If we adopt a positive view of humanity's future, decades or centuries from now if we assume that humans will have been able to establish a permanent or semi-permanent presence in the Solar System, we will have a variety of new interaction challenges that so far have only been explored by science-fiction. One of these is the communication delay across interplanetary distances due to inescapable physical limitations. Even across the relatively "small" distances (on a galactic scale) of our Solar System, a signal needs to travel at the speed of light from the Earth between five and twenty minutes each way to reach the planet Mars (the time varies depending on the relative distances between the two planets). This problem has been notably popularised by books and live action films or show like The Martian (2015) or The Expanse (2015) and many others, where protagonists have to plan around the delay in communications.

Compared to instant messaging here on Earth, across interplanetary distances it will become impossible to hold real-time conversations. This poses a considerable strain in how communication between people happens. Nonetheless, it represents an interaction challenge that people in the future will need to address.

To investigate how this delay would affect user behaviour and draw insights on the design of such far-future interaction scenario using VR, we developed an immersive "enactment" of a scenario, based on a methodology we proposed *et al.* [20]. Immersive Speculative Enactments (ISE) are exploratory user studies in which participants are immersed in a


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Figure 1 The exterior of the Martian outpost used in the study.

Virtual Environment (VE) depicting a possible future, in this case one where an extra-terrestrial outpost exists. Participants of the ISE were required to perform a task given to them by the *"Mission Control"* on Earth, and report back on the outcome. We experimentally manipulated the duration of the time delay by having one group of participants perform the task in a Martian outpost (see Figure 1) where a message required a round-trip of at least ten minutes of real time (which, for practical purposes, was based on when the two planets are at their closest distance). A second group experienced the same scenario but set in a Lunar outpost (see Figure 2) where the delay was more negligible, less than a four second round-trip.

Finally, we report the qualitative results of a thematic analysis based on the enacting of the Interplanetary Communications ISE. The behaviour users exhibited differed from what they imagined would do in a real-life situation. The main factors point towards the VR experience lacking a sense of "urgency" and to the VR system not providing consequences for their interactions. We thus discuss this and other themes emerged from our analysis and the implications they might have for designers of immersive VR experiences and enactments.

2 Related Work

Here, we give an overview of relevant related work, discussing speculative approaches, along with how other works have studied the intersection of HCI and space technologies.

2.1 Immersive Speculative Enactments

ISEs [20], a methodology originating from other non-immersive HCI speculative methods. The aim of ISEs is to use the results of the analysis of the user from these VR studies to provide insights that can potentially be applied in the real-world and to stimulate discussion on these topics.

Conventional speculative methods include *Design Fictions* [3] are a method that consists in describing a possible future or artefact, and using this opportunity for subsequent reflection. User Enactments [18] represent a more hands-on approach in which the possible future is

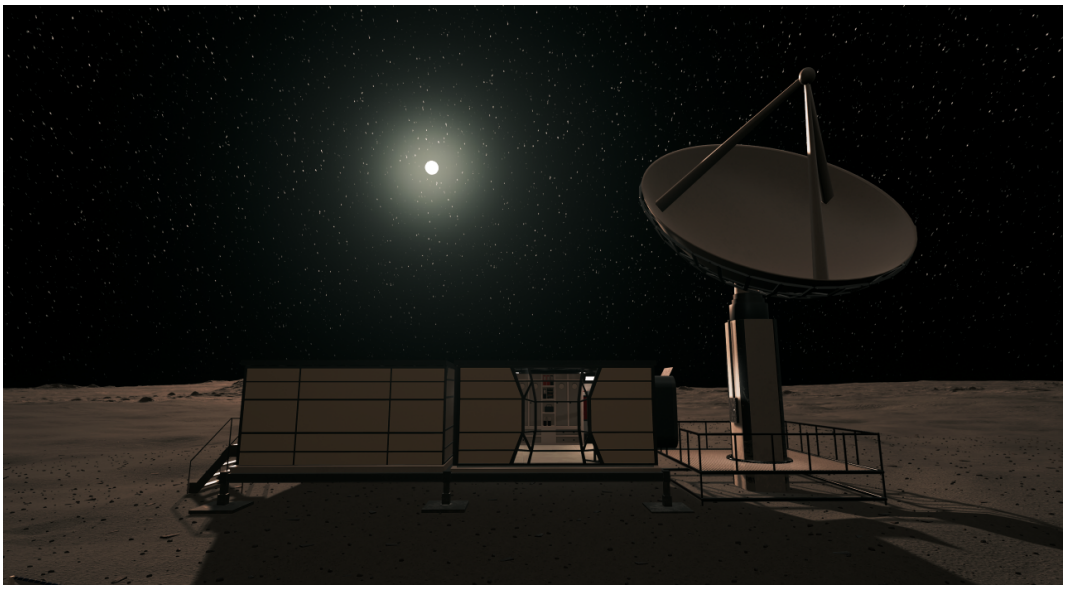

Figure 2 The communication dish seen from the surface of the Moon.

enacted in the real-world. In Speculative Enactments, use speculative methods and real actors to engage participants in reflecting about a fictional artefact or scenario in the real-world. ISEs combine these methods but use VR to provide a realistic representation of the possible future the experimenters had in mind. This approach benefits the limitless potential of VR in allowing participants to experience a vivid recreation of the speculative scenario, but also "locks in" the imagined future to how the experimenters designed it, whereas in other conventional methods user imagination can play a bigger role.

Other examples of ISEs include using VR to analyse the usability of an artifact [28], to evaluate a system to support users in remaining aware of out-of-view incoming traffic [28] and to investigate increasingly more distant future scenarios and technologies [6, 20].

2.2 HCI in Space

The intersection of HCI practices and their application in the domain of space exploration constitutes a nascent trend. With the increase of the capabilities provided by contemporary VR headsets, a number of studies have sought to explore how VR can be used for this purpose. Nilsson *et al.* [16] also used VR to simulate a lunar lander and involved astronauts and other related professionals to critically evaluate the design choices, in a simulated lunar environment. Their results align with the ones we obtained through this ISE, in identifying the limitations of the level of immersion provided by VR. In a related study [7], the use of physical gloves to enhance the believability of the simulation was also evaluated, showing positive effects on presence. Using more conventional means, Freitas *et al.* [11] developed Conversational User Interfaces to support astronauts operating in extraterrestrial habitats, using a Wizard of Oz to provide guidelines for such systems. In [27], Vanderdonckt *et al.* investigated the suitability of existing interaction design frameworks for application in extra-terrestrial settings, suggesting future research to take a greater focus on the analysis of these themes.

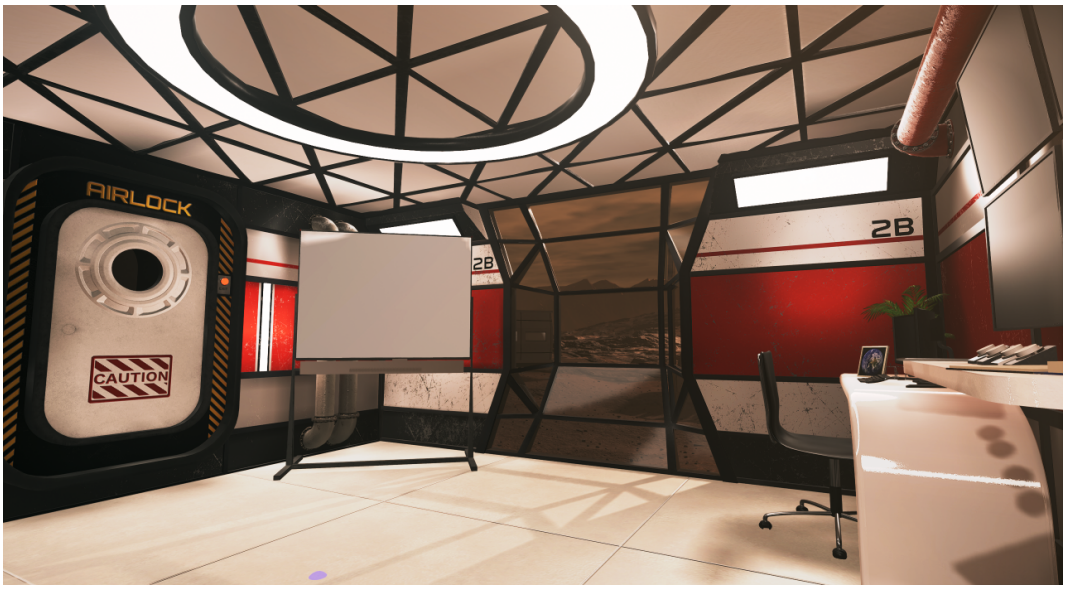

Figure 3 A view of the interior of the Martian habitat, showing the interactive whiteboard and screens. The airlock on the left leads to the exterior.

3 Design of the Outpost

The extra-terrestrial outposts were designed using the Unreal Engine. They consist of an exterior area with a hydroponic module, a solar panel array, a communication dish, and the main habitat (see Figure 1). The difference between the Lunar and Martian outpost is the appearance of the exterior terrain. The Martian environment was based on an asset pack purchased from the Unreal Engine Marketplace, "Mars Landscape"[1]. From it, we also derived a similar landscape material to depict the appearance of the Lunar regolith. The two VEs are essentially identical, save for the appearance of the terrain. Mountains were added in the background of the Martian environment for aesthetic purposes and were not generated from the terrain data.

3.1 The Habitat

The design of the interior habitat (see Figure 3) was inspired by a NASA-sponsored 3D Printed Habitat competition ran in partnership with "America Makes". The goal of the challenge was to design habitats that could be built using 3D printers which would use local materials or even a mission's waste products. It must be noted that designs for deep space habitats are often envisioned as cylindrical. However, to utilise the space available in our VR lab to its fullest extent, we decided to model the room in 1:1 scale with the physical bounds where the ISE would take place, a room of $4\,\text{m} \times 4\,\text{m}$. Although the presence of a glass wall showing the exterior might not be realistic for an habitat built with today's knowledge, we decided that seeing the planet's exterior might reinforce the illusion of being there.

Transition to the exterior was handled by touching a button placed next to the airlock. This would trigger a teleportation to the exterior area. In order to reuse the physical space, users found themselves rotated 180° after the teleportation. This allowed us to reuse the

[1] Mars Landscape: `https://www.fab.com/listings/2aabc0be-3ec2-49cb-afd3-e598b47e1019`



Figure 4 The habitat as seen from the other angle, showing the interactive cabinets and the "VR in VR" station on the right.

4 m × 4 m physical area for the exterior. This area, delimited with railings, contained the manual override panel to control the communication dish's orientation – the objective of the task (see Figure 5). Once outside, the user's view was modified to give the semblance of wearing a helmet, but due to time and resource constraints we did not implement a realistic airlock transition nor suit-wearing interactive behaviour.

3.2 Interaction and Speculation

Where conventional enactments use materials such as short videos, in-person events, brochures, etc. to prompt the speculation [8], the immersive analogue consisted in a sandbox VE. The VE, through its graphical design, reinforces the boundaries of the enactment, while the interactive elements of the VE allow the users to express themselves and improvise their reaction. These elements together provide the lens through which we can observe a glimpse of their speculative behaviour in such a situation.

Since the time spent by users who decided to engage with the task would represent only a minor proportion of the total immersion time, we brainstormed about what kind of activities a prospective space colonist would be interested in doing, while waiting from a reply from Earth. The design of the environment had to support the open-ended nature of the enactment. While the narrative suggested a "mission" the user had to complete, they remain free to completely disregard it.

For the design of the interactive aspects, We were inspired by contemporary science-fiction games such as Deus Ex: Human Revolution or Prey (2017), which portray sequences in otherwise ordinary environments. For example, the initial "fake" apartment of the protagonist in Prey, or Adam Jensen's or V's apartments in Deus Ex or Cyberpunk 2077. With some notable exceptions, these do not usually provide the player with major gameplay activities or puzzles, but rather they provide contextually appropriate interactive elements that players would expect to find in such settings. For example, food items, reading materials, watching the TV, checking the mail on a computer, taking a shower, etc.

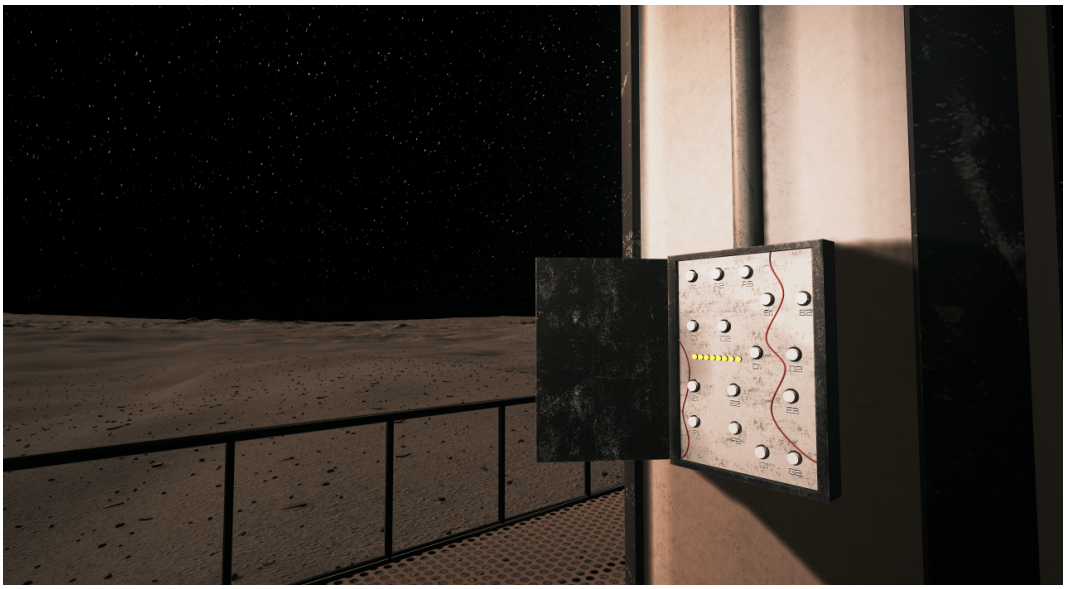

Figure 5 The manual override panel, as seen from the exterior of the Lunar outpost.

Similarly, we added several interactive objects that could be manipulated via the natural interaction metaphors [15] commonly found in VR games that leverage the availability of 6-DOF controllers. Thus, small objects were not static, but could be grabbed by the user and used to interact with the environment (e.g., a pen to write on the whiteboard) or inspected more closely (e.g., an ebook reader, a tablet with instructions on the task). The environment also presented various other interactive objects such as: a music player, drawers that could be opened by grabbing the handle and pulling towards oneself, screens that could be switched on and off, reporting readings from the nearby hydroponics farm (which was inaccessible) and solar panel array (see Figure 3-4).

3.3 The Scenario: Mission to Mars (and to the Moon)

The scenario depicted in the ISE had users play the role of colonists on another planet. The experience was purposely set in the hypothesised early stages of human space exploration. Participants were not intended to represent the "first humans" on Mars nor the the first to return to the Moon after the 20th century. In the scenario, it is assumed that a (semi-) permanent presence on either Mars or the Moon has been established and that some initial infrastructure has been built as well.

We created a plausible backstory that we relayed to each participant before starting the experiment. Participants play the role of technical staff being sent to perform routine maintenance to an automated outpost. A distinction between an imagined larger settlement and a more isolated outpost was made in order to explain why participants would find themselves alone in this location.

The VR experience begins inside the habitat. After one minute in the VE, a notification of an incoming message will be shown on the screens (Figure 3). The message urges the participant to walk towards the "VR Communication station" (Figure 4) and use the headset provided. This additional "virtual" VR system provides a *VR-in-VR* experience, where they will be able to play the message back, and eventually reply. The motivations behind the choice of using a second layer of VR are discussed successively. The message instructs the participant to go outside and operate the manual override of the external communication



Figure 6 The *VR-in-VR* environment, from which participants could listen and reply to the message sent from Earth.

dish's control panel (see Figure 5). The mission control on Earth requires this to be done in order to correct the course for an incoming delivery on the surface of the planet. The message contains an animation of a sequence of buttons they need to press on the device's control panel located outside, in order to re-orient it. It also informs them that a reference of this information can be found on a (virtual) tablet located on one of the desks, which they can pick up to remind themselves of the correct sequence.

Once outside, they can open the panel by holding the trigger and performing a pulling motion with the controller. They can press the buttons by colliding the controller with each one. By entering the correct sequence, the dish will rotate to the needed position. A series of coloured LEDs informs the user whether the sequence they have entered is correct or wrong, in which case it resets and they can try again. After performing the task, participants are instructed to return inside, send a response through the VR-in-VR system, and then wait to receive a confirmation back. In the Lunar environment this confirmation arrives almost instantaneously, whereas in the Martian environment the communication was artificially delayed until 10 minutes had elapsed. This duration was chosen to simulate a situation in which the two planets were relatively close, to keep the duration of the experiment manageable.

3.4 VR Communication System

We opted for this solution for two reasons, one practical and one design-oriented. Firstly, because the only actual example of communication between parties located on different celestial bodies is represented by the Apollo radio exchange. In *hard* science-fiction media (that is, media that attempts to maintain a degree of scientific realism – such as in *The Expanse* books and TV show, as opposed to the *Star Wars* universe), the *thopos* of interplanetary (or

even interstellar) communication is represented by asynchronous video message fragments that are recorded at one end, then sent to the receiving end. Due to the lack of resources necessary to hire professional actors to record the messages originating from Earth, we considered this alternative.

We considered the feasibility of such a VR communication system based on current technological capabilities. For instance, NASA's Curiosity rover can establish a direct link with Earth at a rate of 32 kB/s. When routing data through the Mars Reconnaissance Orbiter, transmission speeds can reach up to 2 MB/s, whereas the Odyssey orbiter supports rates ranging from 128 kB/s to 2 MB/s. However, these connections are constrained by power availability and orbital alignments, limiting the transmission window to just eight minutes per Martian sol. The Mars Reconnaissance Orbiter then forwards data to Earth at a maximum rate of 750 kB/s.

Given these constraints, the direct streaming of audiovisual data from Mars to Earth would likely be impractical in the early stages of human colonisation, particularly for non-essential communication. The establishment of a deep space *Interplanetary Internet* might alleviate this problem [1]. Transmitting short encoded messages, which would then be interpreted and reconstructed locally through the help of an embodied or conversational user interface might feel more "natural" for the user, as also investigate dby Goncalves *et al.* [11].

In our implementation we assume that the outpost provides such an "AI" system. Upon receiving a message from Earth, the AI, personified by a three-dimensional avatar (see Figure 6) can voice it and thus relay any instruction to the user of the VR station. This introduces an additional VR system in the VR experience itself (a similar approach was used as a metaphor for a VR transition technique [17]). Participants can "log into" this VR-in-VR system by walking towards the VR station, grabbing the virtual headset and moving it towards their head. They can remove it by performing a similar, but inverted, motion. The VR station is shown to the right side of Figure 4, under the green light. Once in the system, a 3D User interface allows the user to interact with the local "AI" who reports the received message and communicates it through synthesised speech recordings.

Although the data rate will be less of a problem in Earth-Moon transmission, to provide similar conditions across the two scenarios, the VR-in-VR system is also present in the Moon scenario.

4 User Study

The main aim of the study was to enact a VR scenario that prompted participants to confront themselves with the idea of inhabiting planets other than earth, and encountering delayed interplanetary communications. By enacting this scenario, we wanted to explore, from a qualitative perspective, this novel speculative approach, and understand whether the overall scenario and the duration in the delay between communications would affect our participants' behaviour. To achieve these aims, we designed the narrative-driven VR scenario previously described. We ran a between-groups test in which the independent variable was the delay duration, and thus either the Martian or Lunar environment.

4.1 Participants

We recruited 26 volunteer participants (19 Male, 7 Female; $M = 29.23, SD = 5.43$) randomly assigned to one of the two groups (13 in the Martian environment, 13 on the Moon). They were asked to rate their average experience with VR technologies on a scale from 1 *(use VR rarely)* to 7 *(use VR multiple times per week)*, with a mean self-reported rating of 3.19 ($SD = 1.79$).

4.2 Task and Procedure

The study protocol was reviewed and approved by our University's Ethics Review board. Participants were instructed that they would receive a communication from Earth asking them to perform an activity outside. We told them that they were free to act as they wished. We added a maximum time-limit of 20 minutes after receiving the first message, in the event that participants refused or were not able to complete the task as described. However, this limit was never reached and every participant was able to finish the task.

To avoid the so-called "wow factor" experienced by people being immersed in VR for the first time, participants were first required to undergo a tutorial session instructing them on how to interact with the objects, how to move, and how to open doors. The assumption is that, were they actually in that situation, they would not be unfamiliar with the equipment present therein. After completing this tutorial, the actual experiment begins and was then concluded after receiving confirmation from Earth in the Martian scenario, or after spending a further ten minutes in the Moon scenario, in order to have a comparable duration between the two conditions.

4.3 Measures

We recorded each participant's first-person interactions in VR. Explicit consent for the treatment and use of the video and audio recordings was collected. After the conclusion of the experiment, participants were required to fill-in two questionnaires: the Slater-Usoh-Steed Presence questionnaires [25] and Kennedy's Simulator Sickness questionnaire [13]. Successively, we conducted semi-scripted interviews with the participants based on the following list of topics, and asked further clarifications where necessary.

1. Their experience of the VR-in-VR system.
2. Their behaviour in VR.
3. Whether they felt present in VR.
4. How they felt emotionally while performing the task.
5. Whether they would behaved differently if the scenario were actually real.

5 Questionnaire Results

The results of the questionnaire scores were analysed using the *Mann-Whitney U Test*. The semi-scripted interviews were analysed through a thematic analysis [5] and are discussed in the following section.

The results of Kennedy's SSQ showed that there were no significant differences between the two environments on the total score ($W = 98,\ p = 0.48$). The average SSQ score for participants in the Martian environment was $M = 20.43,\ SD = 29.12$, whereas in the Lunar environment it was $M = 12.08,\ SD = 12.32$, out of a maximum possible score of 300. There were no significant differences in terms of self-reported Presence ratings between the two environments ($W = 107,\ p = 0.25;\ Mars : M = 2.54,\ SD = 0.97;\ Luna : M = 1.92,\ SD = 1.50$), computed as the sum of response indicating a score of 6 or 7 scores on six total questions.

6 Thematic Analysis

We transcribed all the interviews and generated a document consisting of 224 question and answer pairs. We then performed an inductive Thematic Analysis [5] on the data. In a first iteration we assigned codes to each unit of data, obtaining a total of 12 codes. In the second iteration, the codes annotated so far were further elaborated to understand the reasons that led participants to behave in the way they did and their overall experience within the ISE.

Through this analysis we identified four main themes: 1) Presence; 2) Sense of Urgency; 3) Hypothesised Real-Life Behaviour; 4) Interplanetary Communications.

6.1 Theme 1: Presence

This theme focuses on the inclination of participants to suspend their disbelief and behave in a way adherent to the scenario's setting. We associated 41 of the total 224 items to this theme, which contains two codes: 1) those participants who did not *a priori* suspend their disbelief of the ISE (23); 2) those who approached it with a "gaming mindset" (18).

6.2 Suspension of Disbelief

Seven participants explicitly expressed that they were sceptical of the potential of the VR experience to provide a believable rendition of an extra-terrestrial scenario. They approached it with a detached attitude. Participant #24 said: *"It's just VR, the worst thing that can happen is that it's game over"*, also echoed by P25: *"I think it's a game, so I came to it like a game. Doesn't matter much."* P9 stated that *"I did not really think [my actions] would really set something in motion."*

Again, P24 questioned whether we should even try to make VR experiences more believable, as the *"the feeling of failure [could] escape the VR and bring it from the outside to inside."* Referring to the potential of negative VR experiences transcending the boundaries and affecting our real-life emotional well-being. For example, the backlash from failing a training simulator drill. P6 motivated their behaviour due to the knowledge that the experimenters were present in the room: *"I would have acted different if I knew that people weren't watching me. I would have talked more with myself."* Further, we did not initiate any conversation, but some participants asked for permissions. For example, P9 said *"I was a bit hesitant to pull that [lever]. If I had not asked anyone if I could pull it, I would have left it alone."* P9 instead considered the element of time as being crucial to the suspension of disbelief: *"Within a small time fragment, how much can someone get convinced that this is real?"*.

6.3 Gaming Mindset

P21 said: *"I was basically just trying everything out."*, echoed by P8: *"Like because I game also so I am used to try to explore a little bit of everything."* These statements reflect the behaviour of those players who enjoy exploring a game to its fullest extent and exhibit completionist or hoarder attitudes [4, 12]. Inevitably, this play style will confront players with the limitations of the game or system. Indeed, due to time constraints, only the objects described in the *Design of the Outpost* section were manipulable. The scene, however, showed several others that might have been interactive. P8 wanted to pick up all the objects in the cabinets (see Figure 4), while P13 wished they could have been able to use the computer (see Figure 3). P13 lamented the difficulty in using the controllers to perform precise movements such as using the crayon to draw on the whiteboard. P18 attributed their desire of interacting with the objects due to a sense of loneliness: *"The feeling that you are on this planet alone.*

[...] There's this sense of loneliness. That's why I was looking at other things to do, like the radio, the books..."

P24 and P26 highlighted the impossibility of sitting down as a strong cause of breaks-in-Presence, perhaps because a chair was shown (see Figure 3). P26 stated: *"[...] one thing that I miss because I really wanted to do is that you cannot sit down. That's something that disconnects you a lot. Because it's something you would normally do. We are not usually standing up in real life."*

6.4 Theme 2: Sense of Urgency

This theme describes the reasons participants gave to explain why they felt they behaved in a way that was different from how they thought they would behave were the situation real. We associated 53 items to this theme, which comprises two codes: 1) those who associated urgency to danger (35); 2) those who associated it to a lack of consequences (18). In the following, we discuss the reasons behind this contrast.

Urgency linked to Danger. Participants reported that they were aware of the dangers of what, if the scenario were real, would arguably be considered a routine task. Participant #4 said: *"It's a difficult situation, it's a different planet, you're alone, everything could go wrong."* However, the behaviour they exhibited while immersed in VR was starkly different. They associated the missing sense of urgency to the lack of explicit danger. P21 said *"I didn't feel [a sense of urgency] but I guess it would work if they sent a message saying Earth will be destroyed in five minutes."* Similarly P10 said: *"Some kind of flashing lights, an alarm blaring in the background. That would create an urgency, but it would also create a more stressing situation of course."*

Lack of consequences. In scenarios where there is no extrinsic danger, five participants mentioned that other sources of tension and urgency might be derived from giving in-world consequences to user actions. Participant #22 mentioned that objects in the VE should be fragile: *"That would probably trigger you to be more careful with the environment. Because I was throwing around my tablet and of course it didn't break."* Participant #23 echoed this view: *"[...] then I would be more conscious because I can do bad things and then they have some effect on how it's going."*

On some level, participants reported feeling anxious due to them being unaware of the potential consequences of their actions, even if what they were afraid of would not have had any negative ramifications. P26 commented: *"I felt a bit anxious when pressing the buttons. Just because I didn't know how dangerous it was."*, while P24: *"I felt some anguish, perhaps 'I shouldn't do that because of consequences.'"* This highlights how implementing actual in-world positive or negative consequences might have a strong impact on their behaviour.

6.5 Theme 3: Hypothesised Real-Life Behaviour

The majority of participants acknowledged that, were they really on Mars or on the Moon, they would have behaved differently. Twenty-six items described the reactions they would have had in a real scenario. Overall, participants felt they would have exhibited a more *mundane* behaviour, saying that they would not have tried to explore and interact so much. P8 and P18 would have read the book during the wait; P9 and P21 would have switched to other tasks; others reported that they would not have interacted with the objects and perhaps just sat down to wait.

P2 and P5 motivated their behaviour by hypothesising that in real-life they would be already familiar with the environment depicted in the outpost or others similar to it, and thus being already experienced, interaction with objects would hold no novelty for them. P24 mentioned the issue of authority: *"I would know whether [exploring or interacting with objects] was allowed or something like that. If it was allowed I would probably do it."*

Two participants said they would not spend so much time outside the outpost. P4 explained: *"I know it's a game about Mars, but I have to go outside. It will be the only experience I will ever have of Mars. I have to go out to see what it's like on Mars."* P8 found it a scary experience: *"I wanted to experience Mars because I won't be able to do so at home any more and yet it was a thrill as well because it is so scary."*

6.6 Theme 4: Interplanetary Communications

This theme resumes the feedback users gave on the VR-in-VR system and the concept of communicating between different planets. Fifty items were associated to the theme.

The system received mixed feedback depending on whether its purpose was understood or not, that is, the idea of reproducing locally the received text communications in place of video or other more demanding media in terms of bandwidth. Those who considered it superfluous would have preferred a video message. Others appreciated the presence of a human virtual character. P7 said: *"I think the fact there was a figure and not just the sound of a voice was helpful."* The feedback we received also highlights issues in interplanetary communications: the temporal validity of these messages. Both parties react on messages that by the time they are delivered refer to a situation already in the past. P26 mentioned that it was not possible to have feedback on the progress of the task or what to do in case the orders they had begun to carry out had been superseded by an evolving situation back on Earth, whose information was still travelling towards them. Four participants did not understand there was a virtual tablet that resumed the information they got via VR, despite it being mentioned in the message. Having redundant information that actively attempts to catch the user's attention seems essential in ensuring the information is conveyed and understood correctly.

7 Discussion

Immersive Speculative Enactments hold the promise of creating a believable testbed for novel technologies, allowing users to explore their existence in a fully virtual space. For HCI research, this holds the promise of extending existing approaches to Speculative Enactments. Here, we discuss our findings with focus on creating environments that users perceive as real, we relate it to the design of simulations and games, and we reflect on aspects of an ISE and its supporting systems that we can improve in order to elicit behaviour that can be studied as a reliable analogue of enacting the scenario in the real-world. Finally, we present focus points for design and deployment of ISEs to support emerging work focusing on space-related enactments.

7.1 Improving Interaction

Based on the results of the thematic analysis, enhancing objects' physics behaviour might improve the believability of the experience. Sjolie *et al.* state that the VE should generally avoid violating the assumption that it is depicting a truly real experience [21]. Simulating object behaviour to a realistic extent would be a further element supporting this assumption.

If being "careless" or behaving in a way that is not adherent to the scenario's context resulted in breaking or damaging objects and thus rendering them unusable, it is conceivable that participants could have behaved differently and tried to be more careful. Especially if these objects were critical to the mission.

In games, those that allow users to manipulate objects usually treat them as indestructible (e.g., Ultima 9 [24], Skyrim [23]). In "The Gallery" [9], a VR game, some objects shatter when thrown. In a non-VR game, users manipulate objects through intermediary expedients (such as pressing a button to "equip" an object), thus breaking an object could be seen as a source of frustration since the user is not directly responsible [10]. Players of egocentric VR games are instead usually directly expressing agency on an object through natural interaction, and thus might find it more acceptable. Further exploration of these insights might have significant implications on player experience and user behaviour. Designing *uncomfortable interactions* [2] as a component of ISEs (such as having to carry weight or wear garments simulating a spacesuit) might also positively reinforce behaviour that is adherent to the scenario.

7.2 Introducing users to ISEs

Differently from conventional enactment, ISEs present a stark contrast between the moment before immersion, and immediately after. Literature has investigated the moment of entering [22, 26] and exiting VR [14]. Introductory sequences are a mainstay of digital games. Analogously, we think that designers should use them to ease the immersion of the participant from a previously real and mundane environment, into the world of a possible future. With reference to this ISE, an example introduction could be a sequence where the participant is aboard a vehicle travelling towards the outpost. Such sequences could also give designers opportunities to relay instructions to participants. Performing the stage-setting directly through the ISE can remove links that tie the participant to the outside world, and thus potentially lower their immersion.

7.3 Usability of Interplanetary Communication System

The ISE presented participants with one specific solution to this challenge, the VR-in-VR system. Based on our observation of how participants used it, the two most critical aspects that future designers should focus on are the recording and conversation support phases. The AI assistant was only used to relay messages, however participants indicated that talking to someone would have been preferable, based also on their own experience of sending voice clips in contemporary instant messaging apps. Using the AI as a listener could provide a less artificial setting. Further, in addition to providing feedback on the delivery of their own messages, such systems should estimate a time window of when a reply might be received. Indeed, we observed participants going back in the VR system or glancing at the screen for such information.

It would also be beneficial to integrate new AI embodied conversational agents based on Large-Language Models that could provide further clarifications based on the communication received so far. Ideally, such an agent would be "trained" on pre-existing mission knowledge. Incoming broadcasts would update the current status of the mission and allow the extra-terrestrial operative to ask further questions, before formulating an actual response to send back. By clearly distinguishing between the real communications and those extrapolated by the conversational agent, the operative could use this as an opportunity for further reflection and analysis. It would also be useful to replicate this approach on the other side, with a

conversational agent simulating what is known about their status back on Earth. Future research should investigate these more complex form of exchanges to provide further insights on interplanetary communications.

8 Limitations and Implications for Space-related ISEs

ISEs rely on the open-ended nature of an enactment [20]: they should present users with a scenario where they are free to engage with the task presented if any, or potentially also be free to disregard it. This, however, increases the burden on the designers as they have to add interactive objects or environments that might not be used in the enactment. We think this is necessary to ensure that there are as few presence-breaking elements as possible. Ultimately, ISEs also serve as an iterative process: by analysing which elements led to user behaving in unexpected ways, the overall fidelity of the simulation can be improved.

Concerning their specific application to space-related scenarios, in particular to extra-terrestrial settings or extra-vehicular activities, our findings are in line with Nilsson *et al.* [16]. Our participants also noted that the ISE did not simulate the martian environmental conditions, or the absence of equipment they might be carrying in such a situation, were it real.

Our participants also expressed the feeling of being "alone". We think this is a promising direction for future work. Depending on the scenario, it is conceivable the participant might not be effectively alone on another planet but have other "local" colleagues (i.e., local to the planet) they could interact with in real-time, in addition to the Earth-based staff. This represents an important requirement for the simulation of scenarios based on extra-terrestrial outposts. Future research should investigate the introduction of other virtual characters in ISEs and study how Wizard of Oz approaches (where these characters are played by the experimenters) impact participant behaviour with respect to AI-based agents.

9 Conclusion

Immersive Speculative Enactment represent a methodological approach that enables experimenters to simulate and analyse open-ended scenarios. They rely on the idea of allowing participants to engage or disregard the logic of the scenario. As such, these require a significant investment in creating the interactivity necessary to minimise the risk of breaks in presence. In return, ISEs allow experimenters to analyse complex scenarios that, especially in the case of space missions, have no other way of being simulated with the degree of fidelity provided by immersive technologies. Our analysis of a scenario based on interplanetary communications presented criticalities in terms of interactive and environmental fidelity, which provided insights to improve later ISEs.

Common to other speculative methodologies, ISEs can also be seen as a "predictive" tool. Its usefulness will need to be evaluated in the context of the distance between the future imagined by the experimenters, and the "real" future that might come to pass decades or even centuries from now. However, by providing the opportunity of reflecting on research questions that will be relevant only in the medium to long term, ISEs have already affected this possible future. In the interest of improving the usefulness of ISEs, future research should perform "retrospectives" to study how the "old" future differed from the future, now present, which might benefit future research questions that researchers who are accustomed to have interplanetary conversations might have.

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Building Trustworthy Cognitive Monitoring for Safety-Critical Human Tasks: A Phased Methodological Approach

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Abstract

Operators performing high-stakes, safety-critical tasks – such as air traffic controllers, surgeons, or mission control personnel – must maintain exceptional cognitive performance under variable and often stressful conditions. This paper presents a phased methodological approach to building cognitive monitoring systems for such environments. By integrating insights from human factors research, simulation-based training, sensor technologies, and fundamental psychological principles, the proposed framework supports real-time performance assessment with minimum intrusion. The approach begins with simplified simulations and evolves towards operational contexts. Key challenges addressed include variability in workload, the effects of fatigue and stress, thus the need for adaptive monitoring for early warning support mechanisms. The methodology aims to improve situational awareness, reduce human error, and support decision-making without undermining operator autonomy. Ultimately, the work contributes to the development of resilient and transparent systems in domains where human performance is critical to safety.

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Keywords and phrases cognitive load, safety-critical systems, human performance, simulation environments, human factors, air traffic control, aviation

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1 Introduction

The work of an air traffic controller is often perceived by the general public as an incredibly intense job, carried out under constant tension and with full concentration. However, based on the author's first-hand experience working GND/TWR at the country's busiest airport, the reality is somewhat different. The job is characterized by variable intensity: periods of relatively well-organized and orderly traffic alternate with rapidly developing peaks that



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demand swift adaptation, heightened focus, and dynamic planning – all while remaining capable of accommodating even greater surges in case of emergencies or irregular operations. [2, 23]. Which is not necessarily easier than constant vigilance [12].

From a psychological standpoint, the interplay between stress and cognitive performance is crucial for understanding how air traffic controllers manage their workload. According to the classic Yerkes-Dodson law [30, 15], which posits that there is an optimal level of arousal for peak performance, both under- and over-arousal can impair decision-making and situational awareness in safety-critical environments [5]. Funke et al. demonstrated that maintaining a balanced arousal level is essential for optimal performance in high-demand tasks [13]. The dynamic operational environment significantly challenges not only technical skills but also psychological resilience, placing a premium on individual differences in stress regulation, attentional control, and coping strategies that profoundly influence performance outcomes [3].

Recent studies underscore the complexity of sustained attention, an essential aspect of cognitive performance. Vigilance tasks are influenced by multiple factors, including arousal levels and individual differences, suggesting that these elements should be integrated into performance assessments and interventions [14]. Furthermore, psychological resilience plays a critical role in navigating the stresses of high-demand tasks. Operators with better coping strategies are less likely to be adversely affected by stress, thus maintaining better performance [27]. Integrating insights from cognitive load theory also enriches our understanding of cognitive performance. Tailored interventions designed through this lens can help sustain operator vigilance and minimize errors during peak workload periods, refining the existing cognitive monitoring systems designed for air traffic controllers [28].

Mental fatigue, defined as a state of reduced mental performance capability [17] can build up unnoticed by the operator [21], contributing as a factor reducing situational awareness (SA) [7]. Increased use of Industrial Internet of Things (IIoT) technology in ATC aims at lowering the probability of human error and improving SA [29]. The sensors collect Automatic Dependent Surveillance-Broadcast (ADS-B) data to clearly display aircraft position data and its callsign on the operator's display [16] in order to minimize the risk of loss of situational awareness and potential runway incursion [9]. Weather sensors collect and broadcast current atmospheric data [10], essential to the flight safety, and aircraft at risk of collision automatically negotiate avoidance maneuvers [8]. Yet monitoring the performance of the crew or ATC personnel is not so widely adopted, with projects in the testing phase, but before production implementation [24, 19]..

Throughout the paper, we frequently refer to examples involving air traffic controllers or aviators – partly due to the widely recognized importance of their condition and situational awareness for ensuring safety, and partly because this area offers opportunities to draw on relevant practical experience. However, the same mechanisms apply in many other areas where a human is a crucial element of a specialized process, and where safety of people or equipment depends on their quick reactions and sound decisions. This includes crane operators on construction sites, heavy machinery operators in factories, surgeons, train dispatchers, or maritime port control, but also space crew and mission control.

2 Methods

2.1 Human factors

The variability of Air Traffic Control Officer (ATCO) workload intensity mentioned in the introduction is not the only factor contributing to potential risks. The controller's work is carried out in a shift system, so it involves disruptions to the circadian cycle, limited

opportunities for rest during the day (e.g. due to the fact that the rest of the family does not work according to the schedule), and finally the individual well-being of a given day, weakness, perhaps the beginnings of an illness.

Although the ATCO is solely responsible for a traffic in his sector, the work is a teamwork – not only in terms of proper, effective communication with the aircraft, but also with other air traffic services or with vehicles moving on the airport's maneuvering area. Most of this communication is not in person – the sender is deprived from the body language, having only an intonation at his disposal. The radio he communicates with, in order to maintain compatibility with historical equipment, has a relatively low bandwidth, and commonly used amplitude modulation is susceptible to interference. For those not trained in listening to aviation talk, it is often completely incomprehensible.

To complete the set, we must also add language problems, pronunciation, and individual accents of the speakers. The trade language of the aviation world is the aviation phraseology, based on English. But it is not colloquial English. The set of words that make up the phraseology is intended to make it difficult to misunderstand the message, e.g. the word NEGATIVE is used as a negation, but for the confirmation we use AFFIRM (not POSITIVE – so that in the case of a broken transmission it is not confused with negation, and not YES, which may be completely illegible). Other factors, such as ineffective or outdated procedures, non-ergonomic layout of the workspace, maintenance works on the infrastructure, temporary changes in the organization of airspace or weather, are additional burdens.

2.2 Simulation environments

Experiences from a two-week experiment in a ground-based lunar facility [26] indicate that even researchers directly involved in the experiment have problems with discipline in regularly completing even short reports evaluating their psychophysiological state [22]. Hence, the automation of such measurements, which allows determining the state of a research participant without the need to directly engage him, increases the credibility and, above all, the completeness of the collected data. But to be able to do so, we need to decide on the environment we will start our experiment in.

Simulation games, which have been available on home computers since the 1980s, recreate selected aspects of reality, such as the work of a pilot or air traffic controller, in a simplified representation, lowering the entry barrier to familiarize with a given area for untrained users (see Figure 1 and 2). Appropriately selected games have been found in teaching programs [20, 6], not only civilian but also military, allowing to practice elements of planning and tactics of a mission without the costs and risks associated with a real endeavor [25]. They provide the opportunity to experience the consequences of decisions made or the chosen method of implementation in the virtual world, minimizing the stress associated with the exercise or decision-making [18] and offering the opportunity to test various alternative approaches in practice [20]. But even though games use simplifications, the emotions they evoke in the viewer are real. The impact of their accumulation, along with fatigue and other factors that affect human performance, can be measured and recorded [18].

The next level is specialized simulators, which reproduce selected aspects of a given task or activity, but without full immersion. An example would be Flight and Navigation Procedures Trainers (FNPT) [11] – they reproduce important parts of the cockpit of a generic aircraft class (e.g. single engine piston land aircraft – SEP(L)) and are certified by the appropriate aviation authority for use as an aid in practicing certain aspects of flight, e.g. instrument navigation and related procedures (see Figure 3). Alternatively, a custom solution can be created at that point (see Figure 5).

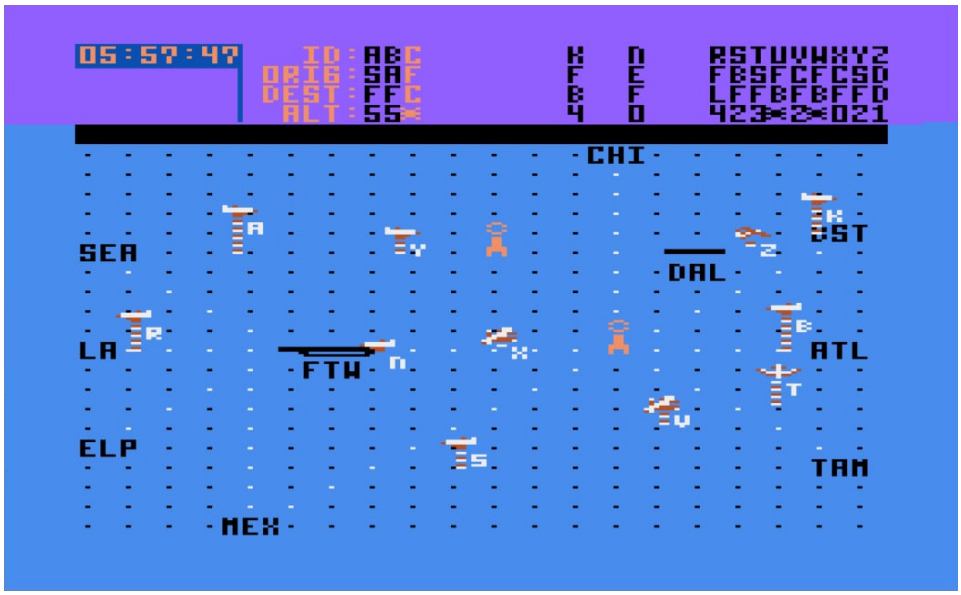


Figure 1 A screenshot from 1985 Kennedy Approach game for 8-bit Atari and Commodore 64 computers, source: `https://fhkd.pl/2024/12/kennedy-approach/`.

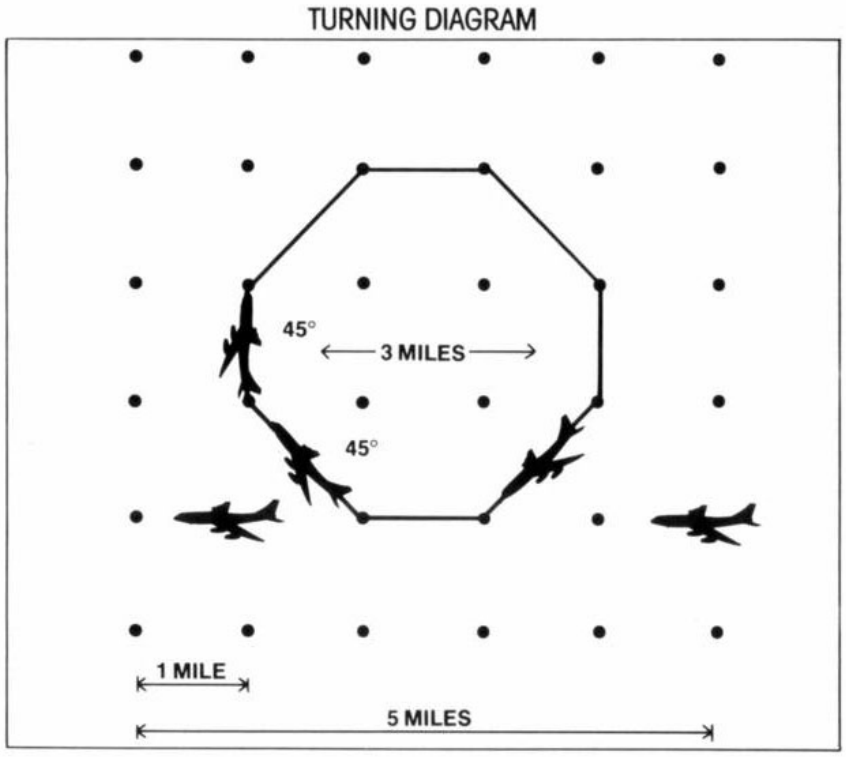
Top tier simulation environments include the aforementioned ground-based isolation habitats, which not only reproduce the conditions inside a remote scientific base, but also the isolation and limited possibilities of leaving the habitat (by convention, or, as in the case of Antarctic bases or those built in remote areas, by practical conditions or a weather window). An example from aviation would be the Full Flight Simulator – a complete, moving cockpit of an aircraft placed on digitally-controlled actuators, with additional installations, e.g. simulating smoke and giving a deep impression of flight in its various phases. For ATCO such example would be a 360 representation of the air traffic control tower, with a live rendered view from outside the windows and fully equipped console (see Figure 4). In order to fully reflect the dynamics of voice contact between the controller and the flight crews, real people, so-called pseudo-pilots, sit at the controls of the virtual machines and communicate with ATCO only through the simulated radio.

2.3 Performance evaluation

According to ICAO Annex 11, the primary objectives of Air Traffic Services (ATS), and thus of air traffic controllers, are to:

- Prevent collisions (both between aircraft and between aircraft on the maneuvering area and other obstructions),
- Expedite and maintain an orderly flow of air traffic,
- Provide advice and information useful for the safe and efficient conduct of flights,
- Notify appropriate organization regarding aircraft in need of search and rescue aid, and assist such organizations as required.

The assessment of the first point is not binary – the mere fact that there was no collision of simulated aircraft during the exercise does not mean success. Violation of the separation criteria established for a given traffic class or space is also classified as an incident. When issuing clearances (e.g. regarding the route or cruising level), the ATCO should take into



To make a 360 degree turn requires a 3 mile diameter and eight 45 degree turns that can be accomplished at each grid dot.

E. INFLIGHT RESTRICTIONS

COMPUTER ACCESS CODE			
COMPUTER ACCESS CODE NUMBER		11	12
RESPONSE	C-64	SID	IFR
	ATARI	VFR	HSI

In order for air traffic to proceed safely through your area several requirements must be met.

1. AIRCRAFT SEPARATION: The first and foremost of these requirements is aircraft separation. You must maintain a one thousand foot separation in altitude between aircraft flying within three miles of each other. Note that planes may fly within three miles of each other if they are separated by at least 1000 feet, or they may fly at the same altitude if they are at least three miles apart. Failure to meet the aircraft separation requirements will result in a "conflict" condition and a possible mid-air crash.
2. BAD WEATHER: Occasionally severe weather (thunderstorms) will move through the area. Planes must avoid this or they will crash.
3. MOUNTAINS: A plane will also crash if it does not maintain an altitude of at least four thousand feet over mountainous areas.
4. RESTRICTED ZONES: Planes must risk being shot down by nervous security personnel if they overfly the Washington Monument/White House.
5. FUEL: Planes carry a limited amount of fuel and will run out if delayed excessively. Planes that are landing at airports in your area have only fifteen

11

Figure 2 An excerpt from the Kennedy Approach game manual, introducing the player to the basic concepts of air traffic control. Compliance with the presented restrictions will be the basis for evaluating the performance after the session.



Figure 3 Flight and Navigation Procedures Trainer certified for single- and multi-engine aircraft procedures training. Source: own resources.



Figure 4 A certified 180-degree view tower simulator for ATCO training. In the foreground, a management station where the instructor can monitor performance in real time and interact with the simulation by initiating non-standard or emergency situations. Source: own resources.

Table 1 Key characteristics of simulation environments of subsequent levels of advancement.

Phase	Characteristics	Example	Advantages	Disadvantages
1	Simplified, approachable by general public.	A computer game.	Inexpensive, easy to recruit participants, easy to learn.	Too simplified, wrong fit to the job.
2	Recreates well core parts of the task	Custom application, FNTP II	Good core mechanics, may be affordable	Training needed, less attractive
3	Full simulation	Full flight simulator, ground based habitat.	Fully immersive, attractive to participants (unique!)	Expensive
4	Real environment	On-the-job tests	Real life verification	Can be disruptive, may require certification.

account the possible loss of communication. Therefore, aircraft should not be issue clearances that may lead to a collision. The sequence of issued clearances should cause the smallest possible delays, and if possible, traffic should flow smoothly and along routes close to optimal ones. When it comes to the readability of the message, we take into account the readability and conciseness of the message, the appropriate reaction to a possible erroneous readback as well as the appropriate rate of transmission.

The more of these conditions we are able to evaluate automatically, the easier the task of matching human parameter measurements and identifying the relationship between them and the operator's performance will be. The level of implementation of the criteria specified for the [25] task combined with the monitoring of the subject's basic parameters (such as heart rate variability, saccadic eye movements, skin conductance, puls-monitoring infrared cameras, etc.) provide insight into the cognitive workload of the subject [18, 19]).

2.4 Four-step Approach

In our approach, we propose a sustainable development method, when we move bottom up from the simplest, approachable solution (see Table 1). The first experiments on human monitoring therefore can take place on groups of volunteers who are not yet the target group of the project. Depending on who the future user will be, the choice of parameters that we want to monitor, and therefore the sensors, may differ. The environment in which it operates also matters – a different scale of integration or power efficiency of the device can be used in a stationary office environment, and another in extreme conditions (e.g. in low temperatures, carried by the operator the whole day, etc.).

When the data starts flowing, it may also turn out that some of the measurements planned to be collected is irrelevant to the task, or duplicates with the ones that are easier to collect. In such a case, it may be reasonable to trim the setup to a reasonably minimum (while ensuring user convenience and reliability).

The choice of a simple simulation environment for a start is important, even if we simplify it to the computer game environments mentioned in Section 2.2 – it will be easier to find volunteers who will play a potentially fun game with our sensors strapped on, than to conduct a boring study. Additionally, the initial briefing can be simpler for a game than for a complex simulator. As the developed solution takes form, we can then think about gradually upgrading the environment, increasing realism.

As our solution matures, and initial elements are validated, more complex environments can be implemented. Through early experimentation and assumption pruning, later stages can focus on those parameters that have proven significant.

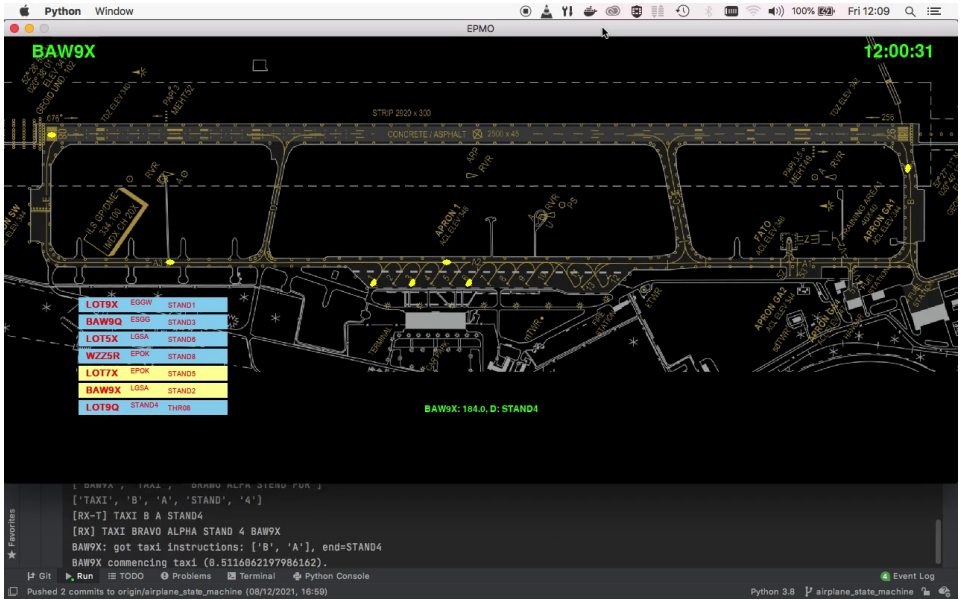


Figure 5 A screenshot from a voice-controlled custom GND simulator built in-house for the purpose of the voice sentiment analysis as a part of authors' ATCO fatigue early detection research.

Approaching the target group with a more streamlined solution later in a game has additional advantages. Technological change often causes resistance from end users, whether because they fear that technology will replace them or because bulky prototypes are inconvenient in everyday use and offer little in return.

3 Discussion

In this paper we explore the implications of cognitive monitoring systems into safety-critical environments. Both technical precision and human factors that subtly influence performance are emphasized. Our multilevel approach highlights the need for reliable sensor-based monitoring while ensuring that these systems adapt to the natural variability in operator responses.

An optimal level of arousal is essential for maintaining peak performance [1]. Slight deviations can affect decision-making and situational awareness, particularly in dynamic settings like air traffic control. We show that monitoring systems should be designed to account for individual differences in response to workload. Data from sensors such as heart rate variability, eye movements, and skin conductance can be invaluable in adjusting system parameters in real time, ensuring that each operator's performance is supported without overwhelming them.

Recent advancements in wearable sensor technology have greatly expanded the possibilities for cognitive monitoring. With continuous tracking of biometric data, sensors now offer immediate feedback that allows system parameters to be adjusted on the fly, in response to stress-inducing situations [31]. The success of such systems depends both on the validity of measures and user-friendly design.

The phased approach begins with the use of simplified simulation environments. Gamification of initial testing allows for a controlled setting to fine-tune the monitoring mechanisms and benefit from large, accessible samples of minimal requirements (i.e. non-professionals).

As the system evolves and becomes increasingly integrated with training simulators or live environments, the need for adaptive and responsive monitoring becomes increasingly evident. The integrated technology should capture relevant metrics and offer feedback that operators can intuitively understand and trust.

We are aware that introducing new monitoring technologies may raise concerns among users, fearing that the new tools will be used to evaluate and eliminate operators based on their constant performance monitoring [4]. But gradually refining the system and emphasizing transparency may make the process more acceptable. Especially since the dependencies discovered during the research – e.g. heatmaps collected during eye-tracking aimed towards fatigue monitoring – can help draw conclusions on improving the ergonomics of the workstation, providing a noticeable improvement in working conditions [19]. The monitoring tools should first and foremost serve as supportive aids to ensure enhanced performance and safety.

In summary, integrating cognitive monitoring in safety-critical applications depends on technical sophistication and deep understanding of human performance. By continuously refining these systems through advanced wearable sensor technologies and a step-by-step implementation process, we can develop tools that respond effectively to both environmental challenges and the subtle variations in how operators perform their tasks. This approach ultimately fosters safer and more efficient operational frameworks.

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Conceptual Design, Manufacturing, and Assembly of a Tall Lunar Tower



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Abstract

This research paper presents the results of a NASA-funded collaborative project between Foster + Partners and Branch Technology that developed the design, manufacturing, and assembly of an optimised 50m tall lunar tower for solar energy generation at the Moon's South Pole. The tower's structure is characterised by a helical diagrid geometry with integrated spiralling rails, designed to enable crane-free manufacturing, solar array deployment, and maintenance. The tower's unique geometry is designed to be compatible with a freeform 3D printing and cellular fabrication strategy, creating opportunities for *in-situ* resource utilisation and load path optimisation. Particular attention was placed into developing a site-specific design that takes into consideration the unique environmental and lighting conditions of the Lunar South Pole. Two demonstrators were fabricated by the consortium: a 1:50 scale functional prototype with a robotically-deployed rotating solar array and a 1:1 scale 5m section of the tower. Both were showcased in March 2025 during the "Earth to Space" exhibition at the Kennedy Space Centre in Washington DC. This project contributes to the efforts of developing supporting infrastructure, such as power and communications networks, which will enable lunar exploration and a sustained human presence on our Moon and beyond.

2012 ACM Subject Classification Applied computing → Computers in other domains

Keywords and phrases Space Architecture, Lunar Infrastructure, Lunar Tower, Additive Manufacturing, In Situ Resource Utilisation (ISRU), Solar Energy

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1 Introduction

The sustained and sustainable presence on the Moon, Mars, and beyond depends on the development of core infrastructure that can enable power generation, life support, and food and water production.

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The design and deployment of space systems is closely coupled to mission objectives, launch vehicle payload capacity, and environmental conditions. As the development of lunar settlements and industries such as mining advance over the coming years, there will be an increasing demand for lunar power and communication systems. Existing and proposed systems are constrained by launch vehicle mass and volume limitations. This can result in complex deployable systems with many moving parts that may be prone to failure and less payload availability for other critical supplies. The development and use of *in-situ* Resource Utilisation (ISRU) manufacturing practices for structural components, outfitting, solar cells, and more, is widely viewed as an important enabling technology for the expansion of exploration, settlement and industrialisation activities on the lunar surface, and their long-term viability [1, 2, 11, 13].

In this context, Foster + Partners and Branch Technology supported by NASA's Small Business Innovation Research (SBIR) Phase I program award, developed the design for a 50m Tall Lunar Tower (TLT) at the Moon's South Pole capable of supporting solar energy equipment. The tower's geometry provides clear load paths for resisting vertical and lateral loads whilst minimising material use through advanced manufacturing techniques. At the same time, it is optimised for autonomous manufacturing and deployment strategies through the integration of support rail geometry that can be used by robotic platforms for vertical movement across the manufacturing, outfitting and maintenance stages of deployment. Lastly, it contributes to the reduction of thermal loading through the use of a permeable diagrid structure; thus, helping it to endure the extreme temperature fluctuations found at the Lunar South Pole. This research paper presents the conceptual design, manufacturing, and assembly of the final tower design and the demonstrators fabricated by the consortium.

Lunar infrastructure precedents

Lunar infrastructure is currently limited to operational and defunct orbiters, landers, and material left from prior exploration programs (e.g., Apollo's Laser Ranging Retroreflectors (LRRR)). Whilst designs for long-term lunar infrastructure, capable of supporting human settlements have been proposed since before the beginning of the space age, all designs remain conceptual (for a detailed literature review the reader is pointed to [10]). Recent Foster + Partners research in this area includes the development of a component-based lunar habitat dome which provides radiation shielding and encapsulates a pre-fabricated inflatable dome [9]. The horizon goal of a pre-fabricated ISRU permanent habitat is predicated on developing sustainable infrastructure required to support such a habitat. Lunar infrastructure required to support long-term human settlements includes the development of environmentally tolerant energy, communication, and transportation networks.

2 Environmental constraints

The proposed site of the TLT, at 89.44° S, 222°E, elevation of 1958m, is along the Shackleton Crater - de Gerlache Connecting Ridge, and is adopted [8]. This location falls within NASA's Artemis 2022 candidate landing site, where the maximum solar elevation angle is approximately 2.3° degrees relative to the surface, with the surface temperature ranging from 100 – 400K. The lunar synodic period of 29.53 days leads to a lunar night of 14.77 days; however, local illumination at the poles varies significantly. These site-specific extreme environmental conditions provide design constraints for the development of lunar infrastructure in the following sections.

Power Systems: Solar Arrays

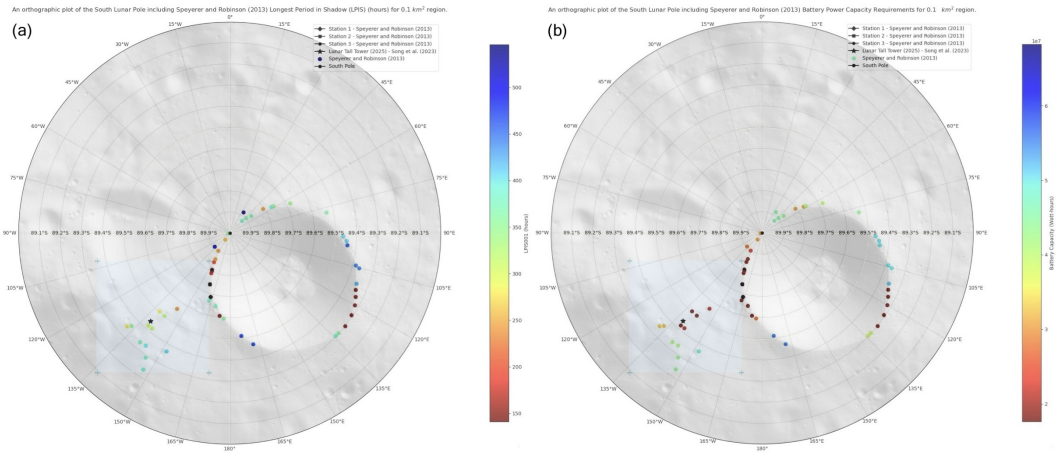


Figure 1 South Polar orthographic projections from 89-90 S°, light blue box indicates the location NASA's Artemis 2022 Connecting Ridge candidate landing site. (a) An orthographic plot of the South Lunar Pole including Longest Period in Shadow (LPIS) (h) targets with TLT location. (b) An orthographic plot of the South Lunar Pole including locations from [7] using a fixed power output 100kW, with location LPIS to defined battery power capacity requirements (Wh).

A lunar habitat will require a power system to support functions such as environmental control and life support systems (ECLSS), lighting, and communications. The Lunar South Pole is of particular interest for future human exploration as there exist regions that provide near constant solar illumination for extensive periods, due to the Moon's low axial tilt (1.5° w.r.t. the ecliptic normal) and the region's highland topography, [7]. While no region on the lunar surface is observed to be in constant illumination (i.e., the Sun eventually sets for all locations), these locations provide the optimal sites for power generating systems using solar cells.

Figure 1 shows the LPIS for a range of candidate lunar exploration sites derived from [7] combined with the TLT suggested location [8]. Long-term sustainable settlements require systems able to survive and operate during harsh lunar nighttime conditions. Comparison of prior studies characterising these conditions provides validation and tower design constraints. We note that the nearest [7] location to the [8] proposed TLT location is at 89.418° S, 221.3°E, with LPIS over 0.1, 0.25, 1, 2.25, and 4km^2 regions centred on the location of 308, 294, 197, 141, and 89 hours respectively.

As part of outfitting a TLT, we consider the integration and deployment of a 100kW solar array which is in line with NASA's SBIR Phase II requirements. Given a location, the LPIS, surface illumination percentages, and a defined power requirement, solar photovoltaic power systems can be estimated in terms of solar array mass, area, and volume [6]. Our calculations assume solar flux = 1367.5 Wm^{-2}, noting that an approximately 3.5% variation occurs over the course of a year due to the Earth's orbit. We also assume a maximum solar elevation angle of 2.3° at the TLT location, and assume that the solar array rotates to track the Sun. A standard conversion efficiency of modern perovskite-silicon tandem photovoltaic cells of 30% is adopted, and a solar cell packing efficiency of 90%. For a 100kW generating solar tower, we estimate the solar cell area to be approximately 271.06 m^2, noting that the area required is likely to be greater due to additional factors leading to conversion inefficiencies, such as radiation damage, micrometeorite damage, and lunar dust contamination. Further details are shown in Appendix A.

3 Geometry

The starting point for the design evolution was the consideration of the unique lunar environment constraints and challenges in conjunction to the adoption of advanced manufacturing methods and particularly of 3D printing technologies. These hold the promise both for maximising ISRU and material efficiency whilst allowing for geometric freedom in defining and realising the tower's optimised form. Initially four key parameters were considered (fig. 2). That is, directionality of printing, materiality, continuity, and assembly/erection process. The resulting permutations of the design typologies were assessed based on Key Performance Indicators (KPIs) including total mass tower, construction complexity, outfitting integration, and resilience. Furthermore, the consortium developed a matrix in which several weighted parameters were evaluated in a systematic way. Preliminary designs considered several typologies such as optimised trusses, cylindrical towers, and post-tensioned systems. The final diagrid system was selected due to its geometrical versatility, process driven design, maintenance-friendly characteristics, material-efficiency, and lastly its potential to reduce thermal shocks across the structure due to its permeable form.

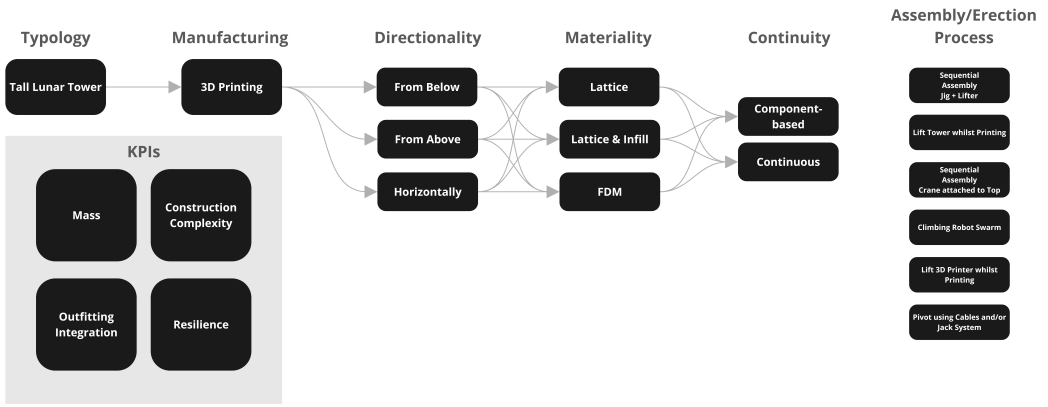


Figure 2 Initial design investigations studied parameters such as directionality of 3D printing, materiality, continuity, and assembly/erection process. The resulting permutations were assessed based on four main KPIs; namely, tower mass, construction complexity, outfitting integration, and resilience.

At the final iteration, the tower's integrated design was developed by considering the functional, environmental, manufacturing, and operational needs of the structure, from construction through to commissioning. In particular, the geometry assumes a diagrid helical form (fig. 3) which can offer clear load paths to resist a combination of loads (vertical and lateral). Specifically, the helical geometry is the defining characteristic of the tower's form as it defines the multi-functional track which enables, manufacturing, outfitting, and solar array deployment and maintenance *in-situ*. The defining dimensions of the TLT are 50m height and 1m diameter resulting in a rather slender tower ration. The computational design algorithm was developed within the Grasshopper platform of the the Rhinoceros 8 CAD software and was based on a custom-made script allowing for a completely parametric definition. This enabled the explicit control of parameters such as diagrid density and dimensions, helical track density and overhang, and structural member thickness and sizing which varied along the height of the tower.

Continuity

One of the key parameters investigated was that of continuity as it would greatly affect both the design and manufacturing of the tower. A continuous approach would allow the 3D printing of the whole structure in one go and directly on the tower location. At the same time, manufacturing resilience could potentially be decreased. This is because one error during the manufacturing process could invalidate the whole print up to that point. On the contrary, a discrete approach would imply increased manufacturing resilience due to the component-based method. However, the components would need to be transported on site; therefore, the assembly complexity could potentially be increased. In other words, the question that arises is where the complexity should be managed: at the manufacturing (component-based and sequential assembly) or assembly (continuous print in situ) stage? In this case, it was decided to opt for the former and 3D print a continuous tower *in-situ*.

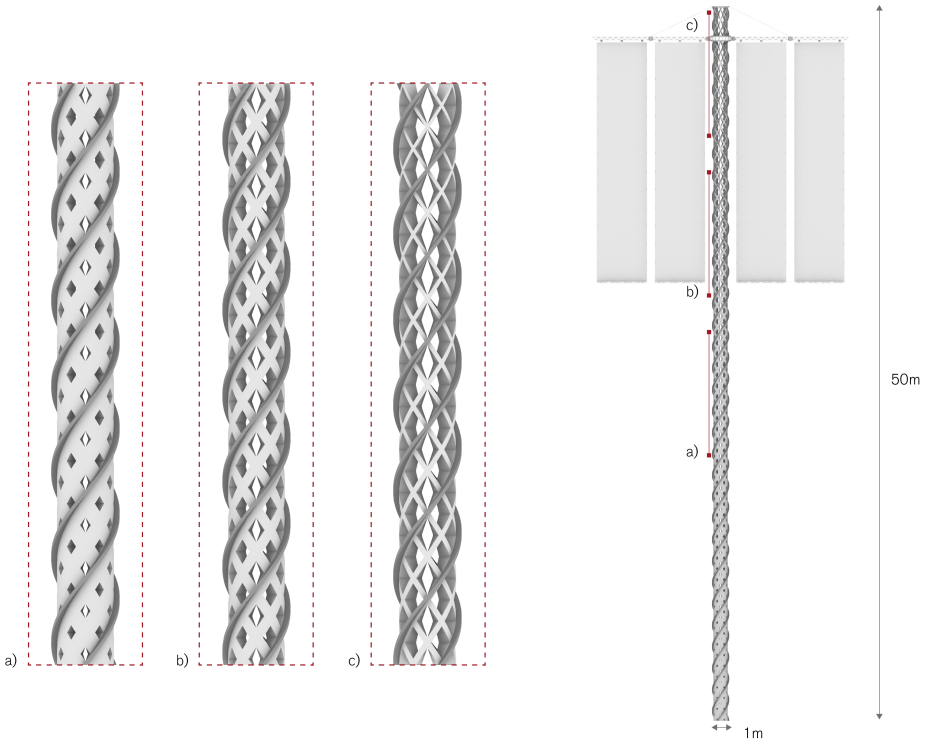


Figure 3 The geometry of the tower comprises a helical diagrid with variable thickness and an integrated helical track which enables the spiralling movement of the robotic system.

Structural analysis and optimisation

Phase I of this project was materially agnostic in the sense that several potential materials and associated 3D printing techniques were considered. The end goal would be to transition the design and manufacturing method to *in-situ* processes; for example, to use locally-sourced metal alloys such as lunar aluminium. To this end, a parametric initial structural analysis framework was developed using the Karamba FEA plugin within Rhinoceros' 8 Grasshopper platform (fig. 4). The geometry input is fully parametric, meaning that shape changes are seamlessly analysed and sized. In this script, parameters such as external loading, material,

and cross-sections can be defined and analysed in terms of deflections and mass tower. Furthermore, a cross-section optimisation method was employed for material-efficient sizing of the structural members.

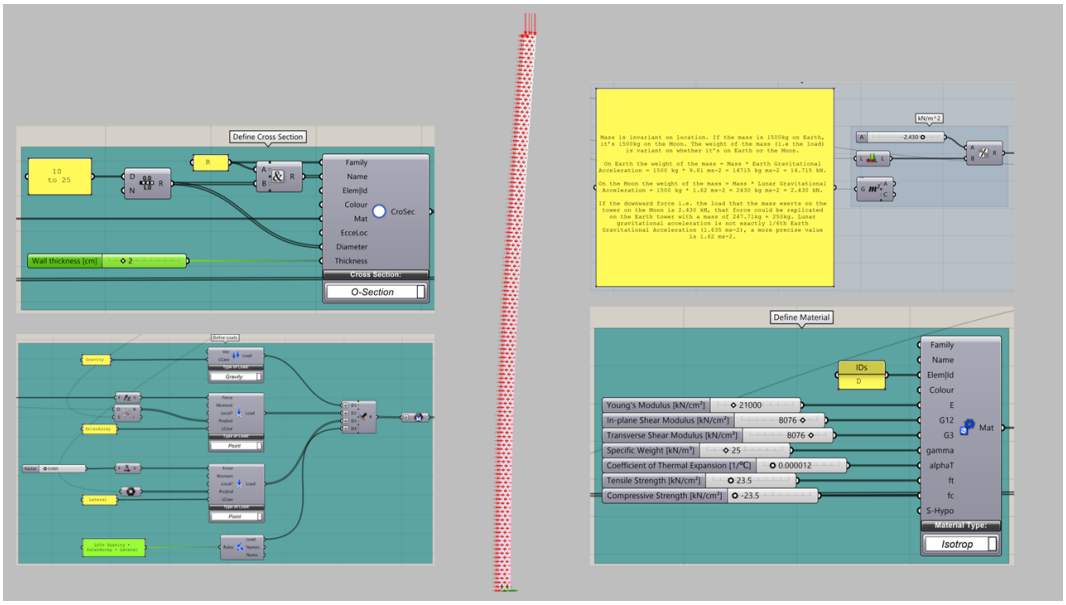


Figure 4 An initial structural analysis script was developed using Karamba FEA which allowed for the parametric definition and optimisation of cross-sections, materials, and load cases.

Outfitting strategy and stabilising ties

The tower's slender aspect ratio, combined with thermal gradient loading and natural hazards (e.g., moonquakes) could present stability risks; therefore, tie integration and outfitting strategies were considered. To this end, a robotic climber system could be used to deploy a tie point ring at a specified height (e.g., mid height for 45deg cables). Furthermore, a system of multiple climbing robots with attached stabilising ties could follow the printing construction stage of the tower to offer stability during construction. Extra tie rings could be deployed if necessary to improve resistance to thermal loading deformation. These could employ systems such as active tension control to manage deflection direction change throughout the solar cycle, as well as compensate for the effect of dynamic lateral loading resulting from moonquakes. However, a disadvantage of external tie points is that it introduces obstacles along the spiral track that could complicate movement, servicing, and maintenance of other ring modules on the tower. An alternative solution would consider internal ties through the core of the tower. This post-tensioning approach could help to remove obstacles along the tower's exterior, allowing free movement of ring modules. These ties would need to be deployed after the tower's completion, potentially leading to instability during construction which could be mitigated through the use of temporary external ties.

Once the tower is constructed, a crane system ring module could be deployed to the top of the tower. This crane system could then be used to facilitate other outfitting activities, such as fitting communications equipment or lighting, as well as serving as the hanging platforms for the solar panel arrays. This strategy reduces the load that must be transported by the climbing robot system along the tower's spiral tracks and allows easier maintenance and

cleaning of the solar panel arrays. Moreover, this system could potentially be repurposed as a deployable crane system for lunar base construction, offering greater heights than previously developed Lightweight Surface Manipulation Systems (LSMS) [3, 12]. Another strategy involves directly lifting the solar panel arrays using the climbing robot system. By reusing the climbing robot system for this phase, the number of robotic systems that need to be transported could be reduced. This however could present a stability risk to the tower, and careful analysis would be need to ensure the spiral fins are not overloaded during the lift.

4 Robotics

TLT construction is intended as a precursor to human presence on the Moon and will contribute towards providing the critical power systems infrastructure required for safe, long duration human missions. During settlement expansion, when humans have begun to populate the stations, it is also desirable to limit or eliminate the construction tasks that people must perform, to reduce the need for high-risk tasks and to allow them to focus on their primary missions. Consequently, autonomous manufacturing systems will play an important role in the future of space development and exploration.

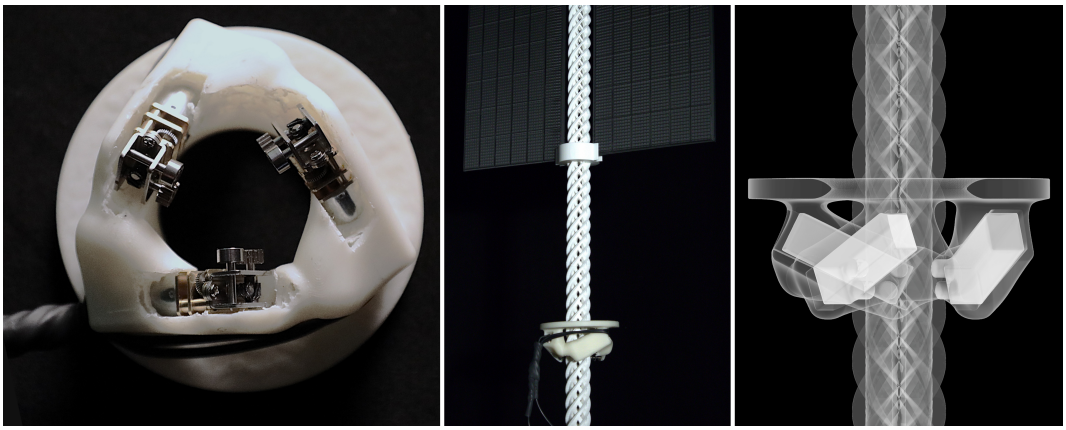
While many autonomous systems have been explored for excavation works and low-height lunar construction, the domain of autonomous tall structure construction is less explored. The NASA developed ARMADAS system [4] uses swarm robot technology to offer a modular construction system using pre-fabricated building blocks, that can rapidly scale to large structures while offering redundancy through the use of a fleet of systems. The applicability of such methods to ISRU manufacturing and diverse infrastructure typologies is an active field of research.

It is envisaged that the robot systems for our TLT will be built upon a base configuration that enables vertical travel along the tower, that can be augmented to specific roles such as 3D printing for construction, manipulation platforms for outfitting, or crane systems for solar panel lifts. At this early phase of the project, the robotic systems a developed conceptually to provide the functionality required to support the proposed manufacturing process with concepts grounded in scale-model mechanisms.

Spiral track geometry

One of the challenges with constructing tall structures on the lunar surface is the absence of conventional lifting equipment such as cranes. The tallest LSMSs developed to date have been focused on off-loading tasks from landing modules, and relatively low-height construction tasks. By utilising an *in-situ* 3D printed manufacturing process, this challenge can be resolved by adapting the tower geometry to serve a functional role in the manufacturing process. In other words, the proposed tower can 3D print itself. To this end, the outer edge of selected helical struts of the proposed diagrid geometry are extended radially to provide an integrated travel rail.

This geometry adaptation provides the vertical lift required for tall structure construction, by providing travel surfaces for climbing mechanisms. When combined with a continuous ISRU 3D printing process, the height of the tower is only limited by the material properties of the construction media. These rails approximately transform the tower into a large multi-start screw, with the pitch and number of starts influencing the force required to raise a platform up the tower, as well as affecting the transfer of load onto the tower. Approximating the spiral track geometry as a multi-start screw, we can identify the relevant parameters of the design and estimate the mechanical advantage and reduction in force required to lift a payload up the tower (see Appendix B for a detailed explanation).



(a) The geometry for the climber ensures clearances for motor installation and fit for spiral engagement.

(b) The climber system is able to raise the printed solar panel array and, depending on the tower parameters, can "deploy" an array through a friction lock.

(c) The resulting motor alignments and generated form conforms to the tower geometry.

Figure 5 The climbing system designed for the 1:50 scale model utilises implicit modelling to find a form that caters to the required motor locations and clearances.

Climbing mechanism

As discussed in 4, the tower's geometry has been designed to provide travel rails that can be used by robotic systems to move up and down the shaft. In contrast to previously developed pillar/pylon/tower climbing systems, this design helps to reduce the force required for vertical travel, though introduces the complication of non-linear travel paths. A parametric model was developed to design an arrangement of motors that conformed to the geometric constraints of the tower's travel rails, as well as the required clearances for the selected motors.

Solar panel deployment strategies

Development of a deployable solar panel system was not within the scope for this phase of the project beyond considering the payload capacity of our design; however, in the interest of developing a functional design, the geometry has been developed to be capable of accommodating the latest advances in lunar solar photovoltaic technologies. Considering the autonomous deployment goal for this design, and the constrained weight and volume payload capacity for heavy lift systems, collapsible and self-deployable panel systems are critical for lunar power systems [5].

5 Manufacturing and assembly

Freeform 3D printing is a methodology of additive manufacturing that seeks to minimize the amount of material consumed. This is achieved by filling printed volumes with Cellular Fabrication (C-Fab®), truss-like lattices as opposed to monolithic, solid layers (e.g., FDM). The process relies on geometry to create strength - shaping structurally efficient forms similarly to how natural organisms are shaped by the forces in their environment. The result is an additive manufacturing method that consumes 95% less material compared to solid-layering. With this technique, Branch Technology has completed projects on four

continents, including several of the world's largest and most significant 3D printed structures to date: from the world's largest-spanning 3D printed structure; the world's largest exterior 3D printed facade; and a full-scale replica of a NASA Space Shuttle at the US Space & Rocket Center in Huntsville, AL, USA. It is the aspect of material efficiency that is in fact the most relevant benefit of C-Fab® in relation to the challenges posed by the lunar environment. This in turn also allows for structural efficiencies that can provide key benefits to NASA missions.

Material efficiency is critical to the establishment of a sustainable human presence on the Moon. This is because the necessary infrastructure will require more resources than are easily transportable or readily available. Most materials used for this purpose will need to either be launched from Earth or harvested in space. However, launching them out of Earth's gravity well is expensive because of launch mass considerations; whereas, harvesting them in space and/or the lunar surface can be difficult. As a result, material efficiency plays a key role to sustainable lunar surface operations. In addition, the trussing lattice structures produced via freeform 3D printing can also improve structural efficiency by leveraging geometries that create a much higher strength-to-weight ratio as opposed to monolithic structures. Specifically, this structural efficiency occurs at both the micro and macro scale:

1. At the micro-scale, only material at the cell's boundary is utilised. This is due to the open cellular structure of the freeform lattice.
2. At the macro-scale, structurally efficient geometries can be achieved. This is due to ability of additively manufactured designs to leverage structural optimization processes unlike other conventional methods in which the design freedom can be constrained.

In the mission to erect infrastructure such as a tall lunar tower for power and communications, construction and assembly process design can benefit from material-efficient methods that can maximize the usefulness of resources across an entire lunar outpost. Branch Technology's C-Fab® and Freeform 3D printing techniques provide a natural inspiration for this typology as they can alleviate launch mass concerns for transported materials and quantity or difficulty concerns for lunar-harvested materials which can potentially be tailored for ISRU in the future. As a result, processes that can be informed by these techniques hold the promise for creating extensible solutions and contributing towards a permanent human presence on the Moon. In the integrated design and manufacturing approach presented here, the tall lunar tower does not comprise prescriptive, prefabricated metal truss components. It is rather 3D printed in-situ with an intrinsic truss-like lattice structure which affords wider design freedom of optimized topologies. Additionally, it seamlessly integrates outfitting capabilities and several potential future applications of the technology.

6 Demonstrators

The consortium fabricated a number of demonstrators during the course of the project. These ranged from small scale 1:50 models, 3D printed at Foster + Partners London, to large scale 1:1 sections of the tower, 3D printed at Branch Technology facilities in the US (fig. 7). Specifically, a 1:50 scale model was developed as a means to evaluate the feasibility of the design, in terms of understanding the manufacturability of the tower design when using an FDM process, and the ability of a climbing model to ascend the tower using the designed-in travel rails. Additionally, the 10m-tall section of the 1:1 scale tower prototype was produced using Branch Technology's C-Fab® process. This showcased the suitability of the tower's design for large-scale fabrication and was exhibited at the "Earth to Space" exhibition which took place in spring 2025 at the Kennedy Space Centre at Washington DC.

7 Conclusion

This research paper presented the conceptual design, assembly, and manufacturing of a 50m tall lunar tower located at the Moon's South Pole (fig. 6) for solar energy generation. The several aspects of the NASA-funded project were discussed including environmental constraints, integrated design, outfitting strategies, structural analysis, robotics, manufacturing, and demonstrator prototyping. Future work will focus on raising the Technology Readiness Level (TRL) of the project by further developing and testing materials, 3D printing methods, and autonomous robotic systems.

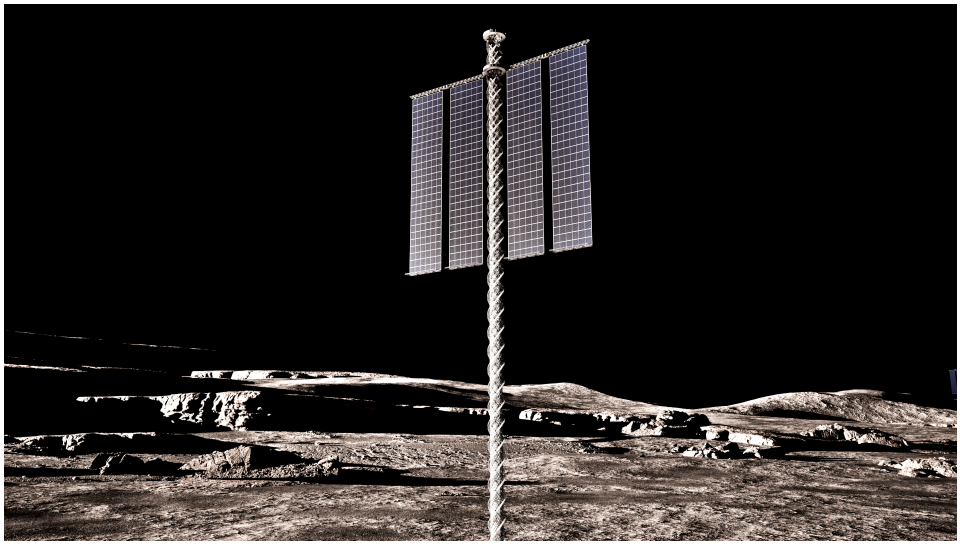


Figure 6 Artists' impression of the TLT at the Lunar South Pole. Image credits: Foster + Partners.

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A Solar Photovoltaics

Power produced from an idealised solar array is given by,

$$P = \phi_{Sun}\eta F_p A\cos(\theta) \tag{1}$$

where P is output power (W), ϕ_{Sun} is the solar flux incident at 1 AU, 1367.5 Wm^{-2} (noting a $\pm$ 3.5% variation due to Earth's orbit), F_p is the packing fraction, the fraction of the solar panel covered by solar cells, typically between 0.85 to 0.90, A is the solar panel area m^2, η is the conversion efficiency, and θ is the angle normal to the Sun. Rearranging Eq. (1), gives Eq. (2), that can be used to estimate the solar array area,

$$A = \frac{P}{\phi_{Sun}\eta F_p\cos(\theta)} \tag{2}$$

As part of estimating the area of the panels for the TLT we assume a maximum solar elevation angle of 2.3° at the TLT location, and assume that the solar array rotates to track the Sun. We assume a standard conversion efficiency of modern perovskite-silicon tandem photovoltaic cells of η=30%, and a solar cell packing efficiency of 90%. For a P=100kW generating solar tower, we estimate the solar array area using the above formula as $A = 271.06$ m^2. The area required is likely to be greater due to additional factors leading to conversion inefficiencies. For example, factors such as radiation damage η_{rad}=0.85, micrometeorite damage η_{mm}=0.96, lunar dust contamination η_{dust}=0.98, Earth's aphelion η_a=0.967, array resistance and diode losses η_{rd}=0.958, UV darkening η_{uv}=0.98 [6], cumulatively lead to a 0.726 factor array efficiency reduction. Additionally considering more conservative estimates on the standard conversion efficiency η=24%, a solar cell packing efficiency of 85%, suggests a solar array area $A = 494.15$ m^2.

B Mechanics of spiral track geometry

To begin analysis of the mechanics we consider the work, W, done by the system. By conservation of energy,

$$W_i = W_o \tag{3}$$

This work is given by the force applied for the distance it acts. For the spiral geometry, considering one full turn of a climbing mechanism, the work in is applied radially, producing a path that travels a full circle, while the work out is applied axially, with one full turn resulting in a travel distance equivalent to the screw lead, l,

$$W_i = 2\pi r F_i \tag{4}$$

$$W_o = l F_o \tag{5}$$

The mechanical advantage for an ideal screw with no friction, MA^*, is then given by the ratio of the achieved output force for the given input force,

$$MA^* = \frac{F_o}{F_i} = \frac{2\pi r}{l}. \tag{6}$$

We can consider the effect of friction on the system by including a friction coefficient, μ, affecting the work efficiency,

$$W_o = \mu W_i \tag{7}$$

Taking the definitions in Eq. (4) and Eq. (5), we arrive at the relationship,

$$l F_o = \mu 2\pi r F_i \tag{8}$$

Assuming a minimum steady state holding force requirement equal to the weight of the payload under lunar gravity conditions, $w_p = m_p g_l$, the force required by the climbing mechanism is then given by

$$F_i = \frac{l m g_l}{\mu 2\pi r}. \tag{9}$$

This represents the total force required to hold a payload on the tower, subject to gravity and friction. For multi-start screw paths, the screw lead is a direct multiple of the pitch for the number of screw starts, N,

$$l = Np, \tag{10}$$

thus considering Eq. (9) and Eq. (10), it can be seen that increasing the number of starts will increase the force required to hold the payload in place, while increasing the friction or radius of the tower will reduce the force required. For a climbing mechanism the uses multiple actuators, the force required can be distributed over the number of actuators, $F_i = \sum_{n=0}^{N_a} F_{i,n}$.

Applying this analysis to a $50m$ tall, $1m$ diameter tower with three screw path starts, $l = 14.25$, and three actuators, and an assumed friction coefficient of $\mu = 1.0$ for an aluminium-aluminium contact surface, indicates a potential force reduction of 47.8%

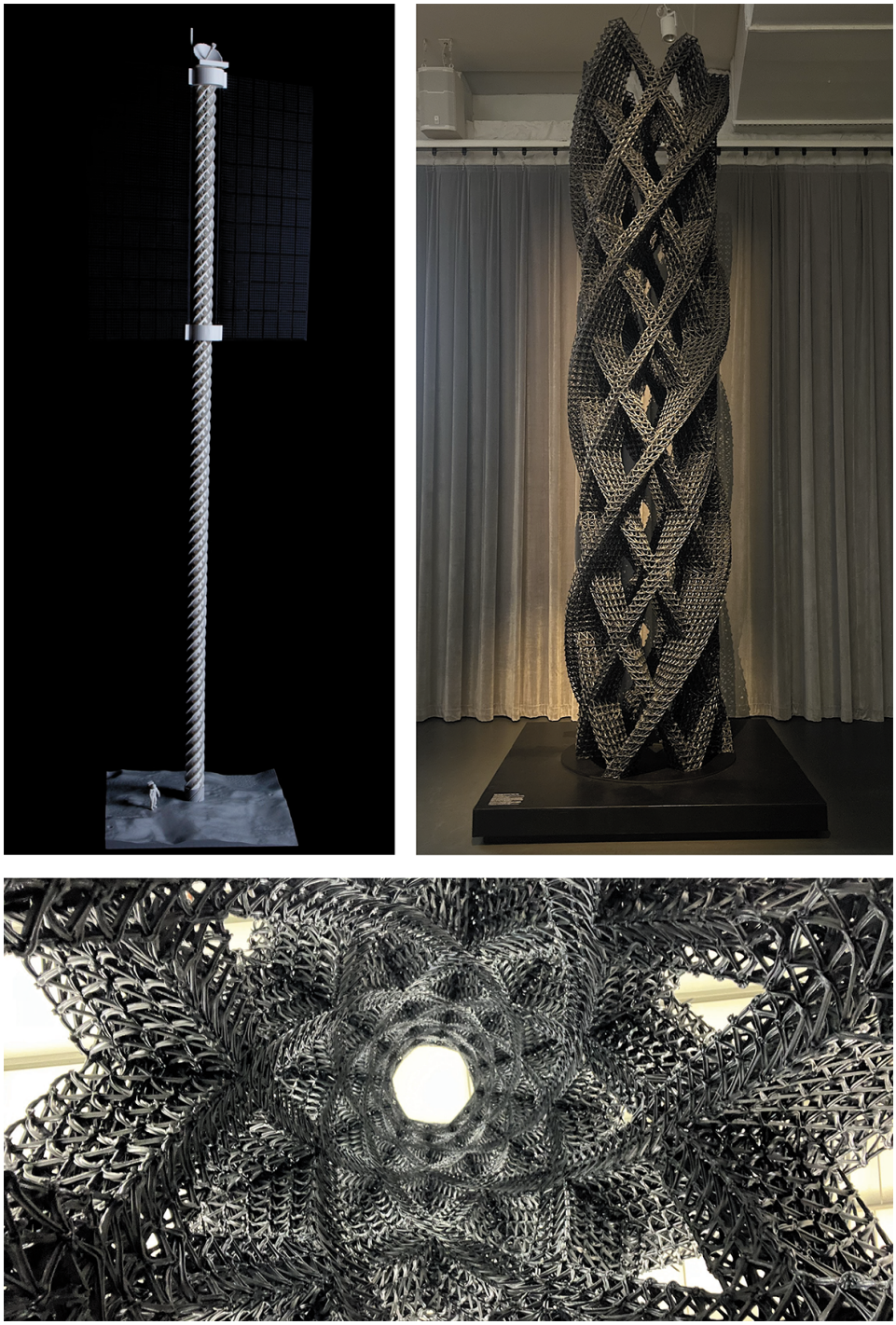

Figure 7 Top left: 1:50 scale prototype which was 3D printed using the FDM method. It included a functional robotic system for raising and lowering the solar arrays. Image credits: Foster + Partners; Top right: Section of the 1:1 scale prototype which was 3D printed by BRANCH Technology using the C-Fab® process, exhibited at the Kennedy Space Centre. Image credits: Foster + Partners; Bottom: Detail of the TLT as viewed from the inside the tower. Image credits: BRANCH Technology.

Exploring the Symbiotic Collaboration Paradigm in Virtual Reality and Its Potential Applications to Human Spaceflight

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Abstract

As the quest to go back to the Moon and beyond continues, preparation for such critical missions relies in part on the use of immersive technologies. Especially, Virtual Reality (VR) unique affordances allow to simulate scenarios in a convincing digitally recreated space. But the potential of VR is not limited to solely emulating real-world environments. Indeed, some works from the Human-Computer Interaction (HCI) community explored new ways to collaborate virtually by inhabiting the same virtual representation, namely an avatar. Taking this paradigm further, one could offer new ways to collaborate between an immersed VR user and an external supervisor being granted access to the virtual environment by way of non-immersive devices like a computer or a smartphone. The non-immersed user could for instance inhabit some body parts of the VR user's avatar to benefit from unique viewpoints and leverage mutual spatial awareness, as well as social interactions, alike a symbiotic relationship that benefits both actors. Therefore, this paper introduces our on-going research project exploring this new paradigm of *symbiotic co-embodiment* as a tool leveraging social presence during supervised embodied sessions in VR. It especially discusses how this paradigm could benefit human spaceflight, both in mission preparation and during spaceflight.

2012 ACM Subject Classification Human-centered computing → Virtual reality; Human-centered computing → Collaborative interaction

Keywords and phrases Virtual Reality, Co-Embodiment, Human Spaceflight, Supervised Training, On-field Activities

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1 Introduction

The efforts from the space sector are turned toward Humankind return to the Moon. The National Aeronautics and Space Administration (NASA)'s Artemis program [8] plans to have crew landing on the Moon as early as mid-2027. Institutions and private companies have historically relied on terrestrial analogues to prepare for space missions [5]. But technology has evolved since the Apollo era, and analogues limitations in terms of emulating specific features of the mission environment can now be overcome thanks to immersive technologies. Virtual Reality (VR) Head-Mounted Displays (HMDs) have the ability to accurately simulate situations with respect to the audiovisual features of the mission concept, such as lighting conditions or object physics. Nevertheless, VR is a complex medium on its own that needs to be carefully controlled to make the most out of it. Especially, as it is oftentimes used for design reviews, learning or training purposes, user experience must be taken into account to

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make the simulation as seamless as possible. Therefore, user-induced perceptual illusions like presence [15] or the Sense of Embodiment (SoE) [17] towards the virtual body must be observed as factors that could increase the fidelity of the simulation and in turn the relevance of VR as a spaceflight preparation tool [11].

Design reviews and training use cases are deemed highly relevant to spaceflights preparation. In this context, the immersive simulations used may support the supervision of the sessions in a cross-platform collaborative way. Indeed, it is common practice to have users immersed in a virtual scenario whereas an external collaborator operates the simulation from a desktop or mobile station. Such settings could benefit investigating new collaboration paradigms like co-embodying the same virtual body [12] to leverage training and social aspects of the collaborative experience [30]. Even if co-locating users in the same body shows promising applications [18], the impact of knowing and sensing that another is inhabiting one's own virtual body remains underexplored. Moreover, cross-platform supervision may benefit from an operationalization of co-localization principia and associated evaluation. We therefore propose the *symbiotic collaboration paradigm* in which a VR user shares her/his avatar with a non-immersed supervisor. The presence of the supervisor within the VR user virtual body would be signified through haptic stimuli to enhance cooperation and mutual understanding. The study we forward would focus on the experience of the VR user in a sense that they experience a one-way co-embodiment situation whose implications need to be understood before being operationalized.

This paper first introduces the relevant literature. Then, the concept of haptic-enhanced symbiotic collaboration is presented before introducing a unique haptic gear meant to foster the symbiotic relationship. A preliminary study evaluating operational aspects of the hardware is thoroughly reported. Then, it introduces the follow-up user study that is meant to provide insights with respect to this new paradigm and its impacts on the VR user experience. We finally present relevant perspectives for Human spaceflight when applying the proposed paradigm, before wrapping up our discussion.

2 Collaborating in Mixed Reality

2.1 Embodied Experiences in Immersive Realities

EXtended Reality XR technologies find a well suited use case for design review and training purposes. This tendency is even more salient in the context of VR experiences, mainly due to its advanced sensorimotor contingency features. The latter facilitates "an inclusive, extensive, surrounding, and vivid illusion of virtual environment" to the users [26]. As presented in the opening of this document, VR is a complex medium on its own. It induces perceptual illusions among users that are referred to as qualia (singular: quale), defined as "a subjective and internal feeling elicited by sense perceptions" [25].

For instance, being immersed through VR technologies elicits among users a subjective experience of *presence*, meaning the sense of *being there* in the virtual space [15, 29]. Slater introduced two orthogonal components to presence, namely Place Illusion (PI) and Plausibility Illusion (PsI), that are sine qua non conditions for the users to experience events happening to them in the virtual place as if they were real [27]. This authenticity of the simulation is what drives new training practices in using immersive technologies.

In addition, the users may interact with the digitally recreated space through a virtual representation commonly referred to as an *avatar*. Experiencing an avatar as being one's own body is conceptualized as the Sense of Embodiment (SoE) in VR [17]. Kilteni *et al.* proposed a framework of the SoE made of three dimensions: *Self-Location*, denoting "one's spatial experience of being inside a body" (distinct from being in the virtual world) ([17, 9]);

Agency, signifying the sensation of having complete motor control over the virtual body, which also encompasses the intention of actions ([7, 16]); *Body Ownership*, referring to the self-attribution of the virtual body [28, 19]. Developing a SoE may appear critical in some use cases. For instance, Gorisse *et al.* [13] showed that users with increased ownership towards their avatar where more likely to protect their body integrity.

Therefore, presence and the SoE appear as two major qualia, on top of every immersive experience, that should be carefully considered when designing for practical use cases in the context of human spaceflights and beyond.

2.2 Supervising Immersive Experiences

As mentioned above, VR could be a perfect ground for design reviews or training activities. But such use cases often involve a supervision setting, in which users are rarely to be left alone with the simulation. Indeed, the aforementioned use cases would imply that one or more operator supervises the immersive session, usually using non-immersive setups for practicality. A concrete example of such practice can be observed when using standalone VR applications that can be monitored thanks to external device screen mirroring features, but that only gives access to the VR user's viewpoint. Some tailored applications go further by providing the supervisor with interaction means, and even a virtual representation. However, collaborating with non-immersed users has been reported to create occlusion problems and peripersonal space invasion in collaborative settings [22]. More specifically, a literature review of collaborative virtual environments proposed by Derouech *et al.* [10] may support the claim that avatar representation tend to be understudied in this context, even if the number of papers considered for the review was limited based on the inclusion criteria ($n = 44$).

Still, a concrete benefit that arises when making the remote supervisor part of the simulation is the potential emergence of a sense of *social presence* [6, 30, 25], encompassing the sense of "being there with another" [6]. Leveraging this quale may benefit positive communication outcomes, like persuasion among others [21]. However, when the supervision is operated through a cross-platform setup, the inherent asymmetry between devices and associated virtual representations may limit non-verbal communication. This latter point is exemplified by Olin *et al.* who designed the mobile user's avatar to signify their inability to use hand tracking and object manipulation by making its hands static [22].

All things considered, there may be alternatives to these methods to leverage collaboration and non-verbal communication in a supervision context, by taking advantage of devices affordances.

2.3 Co-locating Users in the Same Avatar

At the frontier of the virtual and real worlds, Piumsomboon *et al.* [23] explored the question of the supervisor representation through an innovative Mixed Reality (MR) collaboration. Their application allowed for a local trainee in Augmented Reality (AR) and a distant supervisor in VR to collaborate in real-time. They notably reported that having the remote supervisor embodied in a 360° camera mounted on the VR user's shoulder is well appreciated by the latter. This indicates promising benefits for multiscale collaboration with the remote user in close vicinity of the local user. The concept of virtual co-embodiment is crystallizing such an approach. It was recently introduced by Fribourg *et al.* [12] as "a situation that enables a user and another entity (e.g., another user, robot, or autonomous agent) to be embodied in the same virtual avatar". In most virtual co-embodiment settings, two VR users share control over the same avatar. The use of such paradigm shows promising perspectives for motor skills training [18].

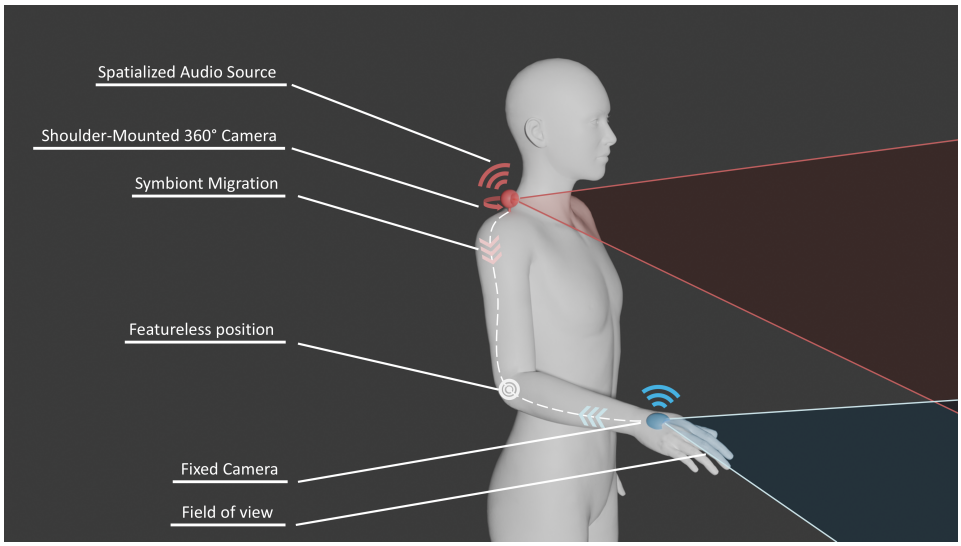


Figure 1 Concept of the features for the symbiotic avatar in the follow-up experiment. The symbiont would have at least two key positions, on the shoulder and on the hand. The shoulder-mounted location would offer a 360°-viewpoint, whereas the camera on the hand would be fixed to allow the VR user to drive the symbiont's attention.

Yet, lot of work on co-embodiment focuses on the impact of control distribution over the virtual body [12, 32, 18, 14]. There is therefore room to investigate the sole fact another is co-inhabiting once own avatar. This may especially appear critical as, to the best of our knowledge, the impacts of co-embodiment on the SoE or social presence are yet unknown. Studying such impacts would require first to make users aware someone is inhabiting their body. Venkatraj *et al.* [32] provided initial insights about mutual awareness cues in their co-embodiment experiment as they operationalized the *perceptual cross* paradigm through haptic vibrations. It consisted in triggering a vibration when both users hand locations overlapped in space. Even if this attempt yielded a negative effect with respect to perceived agency, the result must be considered carefully as the users were not aware of the vibration feedback signification. Moreover, haptics may be beneficial to co-embodiment on the social presence aspect, like when passing objects to each other, or when the haptic communication supplements the verbal one [21].

Finally, the literature would benefit from a first attempt that could lead to operationalize co-embodiment for cross-platform applications. Indeed, as presented in Subsection 2.2, providing the non-immersed operator with an independent virtual representation may cause collaboration issues. Then, making the non-immersed user inhabit the VR user's avatar may help bridge the gap between their device interaction possibilities. Still, the consequences on qualia from the VR user perspectives are still to be explored.

3 Exploring Haptic-enhanced Symbiotic Collaboration in VR

3.1 The Symbiotic Collaboration Paradigm

In an effort to investigate an innovative way to collaborate between a VR user and non-immersed supervisor, we propose a new collaboration paradigm, namely the *symbiotic collaboration* paradigm. It would consist in providing the illusion of a spatially co-located

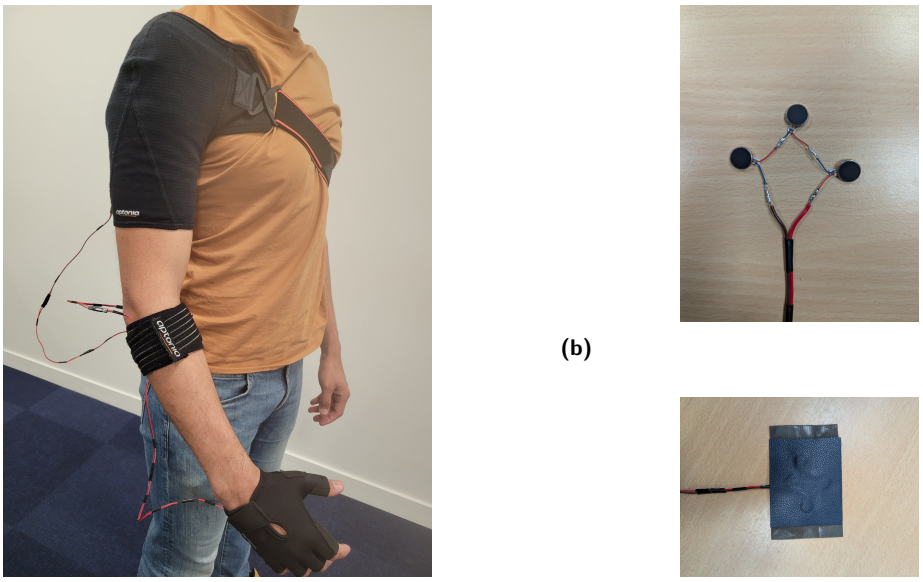
non-immersed supervisor, further referred to as *symbiont*, to the VR user, further referred to as the *host*. This paradigm is inspired by the co-embodiment one in ways that are explained in the remaining of this section. However, for the first iteration of symbiotic collaboration, we convoke a significant difference between both concepts by preventing shared control between the host and the symbiont. Initial design considerations are as follows:

- **The host should have full control over the body:** as a consequence, the symbiont would not have agency over parts of the host's virtual body. However, from the host perspective, she/he may perceive not being in full control of the avatar due to the co-located symbiont in some body parts. On that point, we claim the symbiotic collaboration paradigm requires particular attention.
- **The host should always be aware of the symbiont position:** the main characteristic and cornerstone of the concept we propose is to solely signify the presence of the symbiont user to the host, audio visually and through haptics. By doing so, the symbiont would be provided with unique viewpoints of the host perspective, which leads to the next requirement.
- **The symbiont should be able to freely *navigate* between body parts:** the available migration location should also be communicated to the host to leverage mutual understanding. One could for instance think of a shoulder mounted viewpoint on the host's shoulder that would give a co-located 360° panorama [23], or a viewpoint in one hand to give access to close-ups. At any moment, the host would be aware of the body part inhabited by the symbiont.
- **The host and symbiont should be able to interact in a diegetic way:** finally, providing the symbiont with specific viewpoints, and signifying them to the host with adequate cues, would enable innovative interactions. For examples, one could equip the avatar shoulder with a representation of the 360° camera and embedded speakers that would spatialize the symbiont audio source. Additionally, figuring a screen and speakers in one of the avatar's hand palm would enable live discussion between both collaborators.

Following the aforementionned requirement, we illustrated on Figure 1 a concept of what a symbiotic avatar may look like in the context of the VR experiment we tease on Subsection 3.3. The concept of symbiotic collaboration is hypothetically well positioned to foster collaboration between the host and the symbiont. Even so, it is still conjectural and initial prototypes for such features should contribute to the validation of its advantages and exploration of its limits.

3.2 Haptic System Design and Evaluation

Prior to any evaluation of this new paradigm, it may benefit from the careful design of a device that could help signifying the presence of the symbiont user to the host, namely a "position-aware feedback mechanism" [32]. We designed a haptic device as a candidate to fulfill this goal. The active haptic prop we designed shall be attached to the arm with three key points: on the shoulder, on the back of the hand, and lastly close to the elbow. Each of the aforementioned positions is associated with a cluster of three vibration motors (see Figure 2). Then, each cluster is wrapped between two layers of textile that are sewed together and then to a shoulder patch, a elbow strap and a fingerless glove. An Arduino board provides independent controls for the different clusters. Finally, on top of the active haptic feedback capabilities, the physical hardware may provide additional passive haptic sensations, more specifically the sensation of wearing the gear on the arm for instance.



(a) **(b)** **(c)**

Figure 2 Pictures of the hardware equipped (a) and of a naked (b) and skinned (c) motors cluster. Each motors has a 10-mm diameter and the cluster a 50-mm one.

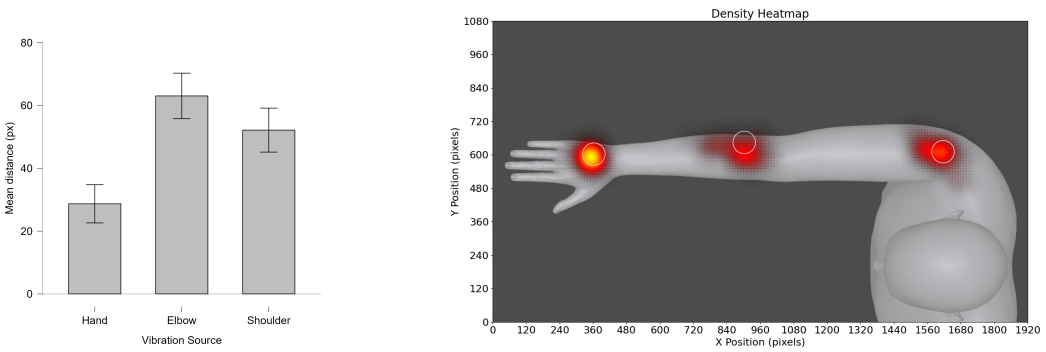
3.2.1 Preliminary assessment

A preliminary experimental evaluation was undertaken to assess the capabilities of our system to successfully draw attention over the selected locations. For this purpose, we led a user study during which participants experienced different vibration patterns and had to report on the location where they sensed it on a schema representing a human arm (see background on Figure 3b). As mentioned in the device description, the three primary sources of vibrations were located on the hand, forearm-elbow, and shoulder. Each participant experienced three times the vibrations coming out of these independent sources in a randomized order, resulting in nine trials for these patterns.

Additionally, this preliminary study was also a testbed for patterns that may signify a smooth transition from the symbiont between locations. To this end, we made either the hand and elbow sources, or the elbow and shoulder sources vibrate at the same time and asked our participants to report whether they felt a stronger vibration toward one of the two sources on the same arm schema. Again each participant experienced three times each of those two patterns in a randomized order. To sum this up, the possible vibration patterns that could be activated through the study were:

- Single: hand
- Single: elbow
- Single: shoulder
- simultaneous: hand-elbow
- simultaneous: elbow-shoulder

Finally, we also made the three sources vibrate in a sequential ascending (hand, elbow, shoulder) or descending (shoulder, elbow, hand) pattern and the participants were asked to order the sources following the experienced pattern. This directionality test gave only one failed trial among all participants, resulting in 99.1% success rate.



(a) (b)

Figure 3 Average distances to the mean point per vibration source (a) and associated heatmap (b). Vibrations' origins are represented by white circles.

Measures

A schema of a human arm (see background on Figure 3b) was displayed as a $1920 \times 1080p$ picture on a tactile screen and participants clicks coordinates in pixels were collected.

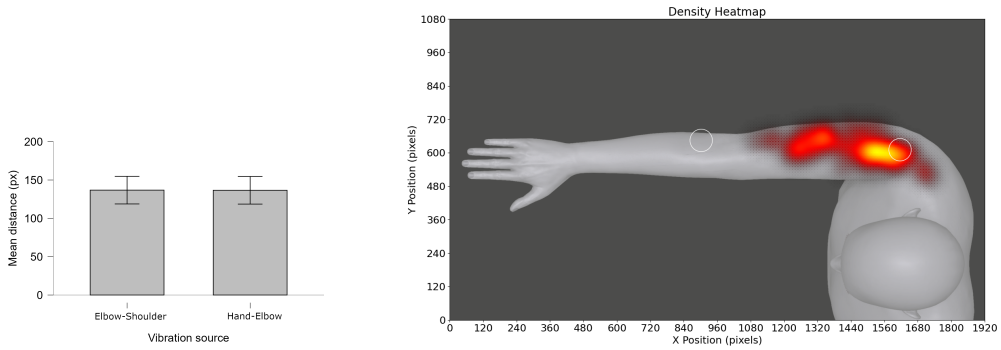
Participants

In total, 19 people (4 females, 15 males), aged 21 to 44 years old ($M = 29.2$, $SD = 7.20$), participated in the experimental study. Researchers and engineers from our laboratory ($N = 13$), as well as master students ($N = 6$) were hired for this early evaluation of the haptic device.

Results and discussion

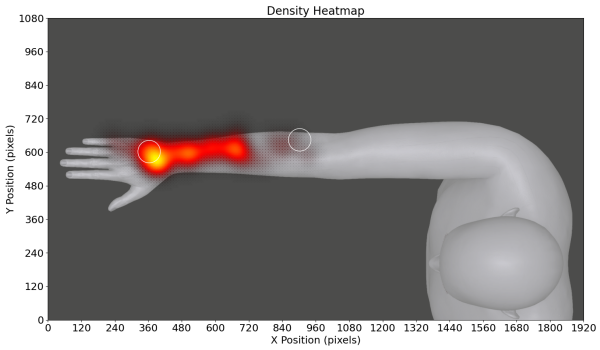
The first part of the analysis focused on comparing the different vibration sources with respect to the subjective perception of the stimuli. Thanks to the point coordinates ($n = 3 \times 19$) participants reported as being the origin of the vibrations using the dedicated touch-screen, we computed a mean location for each source (hand, elbow and shoulder). We then computed the distance between the self-reported points and the mean point as a measure of data dispersion. As the datasets failed the normality test, we performed a non-parametric tests. Friedmann's test showed the vibration source location has a significant effect on the computed source dispersion ($\chi^2(2) = 27.7$, $p < .001$). Conover's pairwise *post hoc* comparisons with a Bonferroni correction showed that the dispersion for the hand source ($M = 28.7p$, $SD = 15.9p$) was significantly lower than for the shoulder ($M = 52.1p$, $SD = 34.2p$, $T(112) = 4.12$, $p < .001$) and elbow sources ($M = 63.0p$, $SD = 36.2p$, $T(112) = 5.83$, $p < .001$) (see Figure 3a). No significant difference was observed between the elbow and shoulder sources. The heatmap on Figure 3b highlights that participants localized more precisely the stimulus origin on the hand than on both the shoulder and the elbow. Most importantly and as expected, the participants were able to localize quite well the origin of the vibrations they experienced.

For the second part of our analysis, we considered the simultaneous activation of two vibration sources. Mean designated locations for the hand-elbow and elbow-shoulder patterns were calculated and allowed for computing the distance of participants' reported points to these mean locations. This allowed us to investigate wether a polarization would occur when



(a)

(b) Elbow - Shoulder.



(c) Hand - Elbow.

Figure 4 Average distances to the mean point for simultaneous sources (a) and associated heatmaps (b)(c).

activating two clusters at the same time. A Student's T-test revealed no significant differences between both patterns with respect to the reported source dispersion (see Figure 4a). However, the heatmap on Figure 4c revealed that the participants perceived the vibrations as originating more strongly from the hand rather than from the elbow. Similarly, the heatmap on Figure 4b revealed that the participants perceived the vibrations as originating more strongly from the hand rather than from the elbow. This is a strong indicator in favor of an experimental setup in which the elbow should not be considered as a primary location for the symbiont, but rather a relay position for signifying the movement of the symbiont between the hand and shoulder through ascending and descending vibration patterns. One reason for these observations may be found in the stronger sensitivity of the hand.

In addition we collected qualitative insights from our participants that raised important design considerations. Indeed, 3 participants spontaneously reported that the fact of hearing the shoulder vibration source stronger than the elbow one during simultaneous patterns may have influenced their answers. For instance, one participant mentioned "the sound can be confusing when interpreting vibrations, especially when it comes from the shoulder which is close to the ear". Another reported that "the sound of the vibrators, especially near my shoulder, can give me more sense of vibrations near my shoulder, and make me ignore the vibrations near the elbow". We thus need to acknowledge this feedback when developing the follow-up cross-platform collaborative experiment, especially as this may interfere with spatialized audio sources in the virtual environment.

3.3 Follow-up Experiment

Building up on our hardware assessment, we plan to conduct a follow-up user study in order to compare the symbiotic collaboration paradigm to a regular cross-platform supervision situation, further referred to as the control condition. By doing so, we aim at investigating whether a symbiotic paradigm between a VR user and non-immersed one foster collaboration and the social presence. In addition, we aim at characterizing the impact of such symbiotic relationship on the experience of the VR user. The collaboration methods will be compared according to two conditions: an omniscient presence of the non-immersed supervisor, and a symbiotic collaboration situation in which the non-immersed user's presence would be suggested to the VR user through audio-visual cues, and through our haptic device. A concept of the symbiotic paradigm implementation is illustrated on Figure 1.

A virtual scenario is being designed in which the experimenter, acting as the supervisor, will guide participants immersed in the VR simulation in completing complex assembly tasks. At the end of each condition, the VR user will have to answer questionnaires assessing their physical presence, sense of embodiment, and social presence as well as items translating how they identify with the avatar in the different configurations. Semi-structured interviews will ultimately be conducted to collect insights about participants experience of the collaboration setup.

4 Perspectives for Human Spaceflight

Space missions are usually articulated around Concepts of Operations (ConOps) defined by Beaton et al as "the instantiation of operational design elements that guide the organization and flow of personnel, communications, hardware, software, and data products involved in a mission concept" [2]. ConOps are therefore concerned with organizing human resources, hardware and software into coherent operations while managing inter-organizational frictions. When it comes to preparing, testing operations, but also training teams to the latter, institutions, like NASA or ESA, as well as private companies, have historically relied on analogue terrains and facilities that features one or more aspects of the actual environment. Natural analogues are oftentimes selected for their geological and environmental proximity with the mission location [1, 3, 5], whereas facilities may be built to emulate specific features of with greater control [5, 31], like reduced gravity using the buoyancy principle for instance. What is mainly seeked when using analogues is a high fidelity with respect to one or more features of the mission environment to support increased evaluation and training of the crews. Fidelity is defined by Silva-Martinez *et al.* as the degree to which it "replicates a real-world, built-environment from the user's perspective by considering form, function and user-interaction" [24]. A prominent example of analog facility is the LUNA building [31], recently inaugurated in Cologne, that is operated by the European Space Agency (ESA) and the German Aerospace Center (DLR). However, analogues may not recreate all desired conditions of the mission. Therefore, eXtended Reality (XR), and more specifically Virtual Reality (VR), has appeared as a low-cost but rather well suited solution to simulate complementary aspects of the mission location, like objects accurate physics or lighting conditions. In this context, LUNA is planned to integrate XR capabilities [31] that could leverage the advantages of the analogue terrain which constitutes a relevant test ground for innovate XR collaboration paradigm applied to space missions. Possible use cases are described in the following sections.

ConOps Review and Training

Preparing ConOps or training crews for these operations often requires a form of supervision from one or more experts outside of the simulation. This question is arising whether it is a rehearsal in an analogue or in an immersive virtual environment. In this context, the use of VR, in combination with physical mockups replicating actual hardware, has already demonstrated advantages for ConOps evaluation. Indeed, Dufresne and Nilsson *et al.* [11] reproduced a well-known and extensively debriefed Apollo 12 ConOp in VR. Subject matter experts invited to take part to the experiment reported an increased fidelity when interacting in the VR simulation with mockups, which resulted in a feedback closer to the one provided by the Apollo 12 crew during mission debriefing. One could then advocate for the acceptance of haptic-enhanced symbiotic collaboration as a relevant add-on when evaluating ConOp in VR by hypothetically leveraging the synergy and understanding between the non-immersed operator and the VR user.

Nevertheless, applications of the symbiotic collaboration paradigm to training situations may not appear as evident. The fidelity of the simulation with respect to real-world conditions is undoubtedly crucial when training for specific ConOps. Besides, negative training caused by inaccurate simulations may have consequences for the astronaut's safety during the mission. As a matter of fact, including a symbiotic collaboration feature in training settings can be difficult when we advocate for a diegetic integration of a concept that may not be perceived plausible with the simulation content. Yet, such feature may not be deemed to remain activated all way through the training session. One could save it for specific rehearsal sessions before training to proficiency. More interestingly, one may also transpose the concept into real life. In fact, real-world applications may not be considered science fiction, as the following section discusses it.

In-Mission Perspectives

Astronauts are not alone when performing an Extravehicular Activity (EVA), as these operations are the most critical and risky when it comes to spaceflight. Indeed, distant operators and support teams are assisting the astronauts in their tasks, while additionally providing social contact through constant communications. Moreover, remote operators have likely access to a video stream from the astronaut's view point. It has even been reported that astronaut attached camera to their arms [20]. In this context, we believe that the symbiotic collaboration paradigm could easily be transposed to real-world situations with the relevant hardware provided to astronauts. Such hardware could for example be embedded in their spacesuits. It may provide a deeper interaction between the remote supervising team and the local astronaut performing some operation. During activities that could last hours on the surface of harsh planetary bodies like the moon, providing astronauts with a constant and perceptible presence may also contribute to their emotional well-being.

On another note, offline Artificial Intelligence (AI) assistants are expected to provide support for astronauts during long duration missions [4]. Consequently, one could take the symbiotic collaboration paradigm one step further by embodying the AI assistant directly in the astronaut's suit, enabling for a new interface that would foster the synergy between the human user and the AI.

5 Conclusion

As a conclusion, this paper introduced the symbiotic collaboration paradigm and its forwarded applications. This innovative collaborative solution may show great possibilities in fostering social presence, not only in virtual settings, but also maybe in real-world use cases. Enhancing the symbiotic co-embodiment situation using haptic stimuli is expected to take the experience to greatness with respect to users' perception. For this purpose, we designed and preliminary assessed an arm-mounted hardware that showed promising perspectives for the follow-up experiment. In particular, it demonstrated its ability to suggest smooth transitions between the symbiont's viewpoints embedded in the arm. This new paradigm and the forwarded benefits it may bring could be well suited for virtual design reviews and VR training applications, which are of paramount importance to the space exploration industry. If the concept is taken beyond the virtual applications, one may consider using the haptic hardware for in-flight applications to leverage social experiences during long space missions. Ultimately, one may couple such paradigm with AI embodied agents to foster collaboration and the astronauts' on-field experience.

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Human Factors and Behavioral Performance Evaluation Framework for IntraVehicular Activities(IVAs) Under Simulated Lunar Gravity: Focus on the Lunar Agriculture Module (LAM)

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Abstract

The Planetary Infrastructure Research Group at the German Aerospace Center (DLR) is developing a Lunar Agriculture Module (LAM) to support sustainable food production and provide Bioregenerative Life Support System (BLSS) functions for long-duration lunar missions. Despite various ongoing research efforts on BLSS development and lunar surface human activities, a critical knowledge gap remains regarding how reduced gravity (0.16g) impacts human factors and behavioral performance (HFBP) during intravehicular activities (IVAs) in a lunar module. To fill the existing research gap, DLR is constructing the Lunar Agriculture Module – Reduced Gravity Simulator (LAM-RGS). The LAM-RGS integrates a Mixed Reality (MR) environment – combining Physical Reality (PR) mockups and Virtual Reality (VR) systems – with a gravity offloading system and multimodal data acquisition tools. This simulator will assess task performance, workload, and biomechanics under simulated lunar gravity conditions to optimize the internal system and rack design of the LAM, minimize ergonomic risks, and improve human-system interaction.

To achieve these goals, this paper presents the experimental design and architecture of the LAM-RGS, introducing a four-pillar research framework consisting of: (1) simulator system development and experimental design, (2) system integration and validation, (3) human factors and performance assessment, and (4) data-driven design optimization. The proposed methodology provides a foundation for systematically evaluating human performance in lunar IVA operations and supports the evidence-based design of future lunar habitat systems.

2012 ACM Subject Classification Human-centered computing → Mixed / augmented reality; Human-centered computing → User studies; Hardware → Sensor devices and platforms

Keywords and phrases Bioregenerative Life Support Systems (BLSS), Human Factors and Behavioral Performance (HFBP) Evaluation, Human-In-The-Loop (HITL), Intravehicular Activity (IVA), Lunar Agriculture Module (LAM), Mixed Reality (MR), Module Design Optimization, Simulated Lunar Gravity

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1 Introduction

Long-duration human lunar missions require advanced life support systems to sustain crews with minimal resupply from Earth. Bioregenerative Life Support Systems (BLSS) offer a lower equivalent system mass compared to traditional physicochemical systems, making them highly suitable for long-term surface operations. The German Aerospace Center (DLR) is currently developing the Lunar Agriculture Module (LAM) to enable sustainable food production and support BLSS functionality for future human spaceflight activities on the Moon.

Although numerous studies have explored BLSS development and lunar extravehicular activities (EVAs), a critical knowledge gap remains in understanding how reduced gravity (0.16g) affects human factors and behavioral performance (HFBP) during intravehicular activities (IVAs) – particularly in tasks related to plant cultivation, system maintenance, and cargo handling. In response to this challenge, DLR is developing the Lunar Agriculture Module – Reduced Gravity Simulator (LAM-RGS). This system enables systematic evaluation of human performance in a simulated lunar environment, thereby informing both hardware design and operational procedures. The LAM-RGS integrates a Mixed Reality (MR) simulation platform that combines Physical Reality (PR) and Virtual Reality (VR) environments to provide high-fidelity, cost-effective representations of plant cultivation and maintenance areas. The simulator also incorporates a gravity offloading system (hosted at the LUNA Facility in Cologne) and multimodal data acquisition tools, including wearable sensors and biosensors to capture physiological, biomechanical, and cognitive performance data under both Earth gravity (1G) and simulated lunar gravity (0.16G) conditions. This experimental facility is designed to assess task performance, workload, and biomechanical strain to optimize the LAM's internal layout and rack system, mitigate ergonomic risks, and improve human–system interaction. The main HFBP study using the LAM-RGS, scheduled for 2026, aims to address the following research questions.

- How does reduced gravity affect HFBP during IVAs related to maintenance, horticultural, and logistics tasks within the LAM?
- How does prolonged exposure to MR environments under simulated lunar gravity conditions affect skill retention and long-term cognitive adaptation?
- How can multimodal data – including task performance, workload (both physical and cognitive), and biomechanical metrics – be integrated to inform the internal layout and operational strategies of a more efficient LAM?

This paper, representing an initial stage of the broader research program, outlines the background and research gap, introduces a four-pillar research framework for the development and application of the LAM-RGS, and proposes corresponding implementation strategies and experimental designs. Furthermore, the LAM-RGS simulator is presented, followed by a discussion of the expected outcomes and recommendations for future research.

2 Background and Research Gap

Bioregenerative Life Support Systems and DLR Projects

The BLSS is a critical technology for enabling sustainable, long-duration crewed missions on the lunar surface by significantly reducing dependence on costly and logistically challenging terrestrial resupply. Accordingly, evaluating the efficacy of BLSS requires extensive testing and builds upon the foundation of numerous prior projects.The performance of BLSS components, particularly plant cultivation systems, has been assessed in various space-based platforms [25, 23], large-scale terrestrial testbeds [31, 14, 15], and mission analogs [29, 16, 7].

Since 2015, the German Aerospace Center (DLR) has significantly contributed to this field, initiating projects such as EDEN ISS [34] in Antarctica. This project successfully demonstrated sustainable food production within a controlled environment under extreme, isolated conditions, providing valuable operational experience. Building on this foundation, DLR is advancing the development of modular BLSS testbeds – including EDEN LUNA [3], and the Lunar Agriculture Module Ground Test Demonstrator (LAM-GTD) [20, 21], collaborating with the Canadian Space Agency (CSA). These current initiatives are specifically focused on maturing technologies and operational concepts required for the eventual deployment and operation of BLSS facilities on the lunar surface.

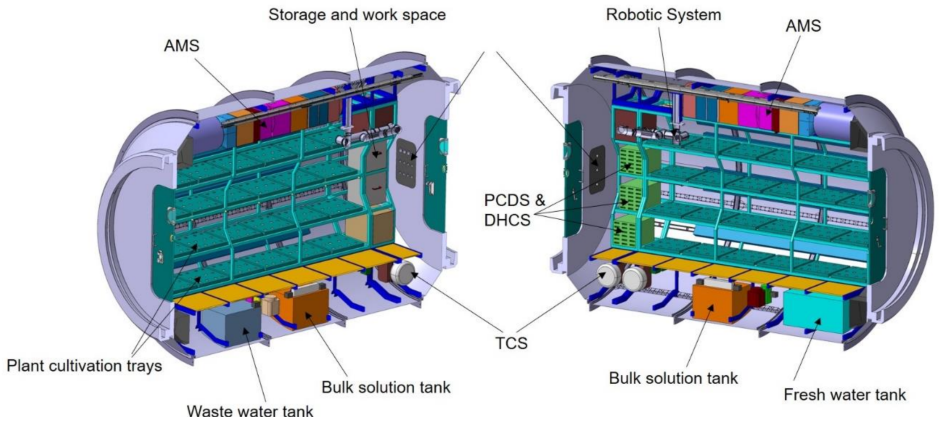

Figure 1 Cross-section of the LAM-GTD's LAM unit [21].

Limitations of Existing Research

Lunar gravity is a critical stressor that must be considered in long-duration human exploration missions. For example, movements such as walking, kneeling, and shoveling under lunar gravity are affected by shifts in the center of mass and reduced gravitational force, leading to impaired balance and increased physical exertion – indicating the need for optimized spacesuit design and appropriate safety measures [28, 4, 8].

Furthermore, the space environment, particularly factors such as altered gravity and stress, significantly impacts key human cognitive and perceptual motor performances, including spatial perception, sense of direction, and mental rotation. These changes can directly lead to a decline in mission performance capabilities and pose safety risks. Such psychomotor impairments have been identified as contributing factors in spaceflight incidents, yet it remains unclear to what extent these observed deficits may change during long-duration missions [19].

Extensive research exists on human factors and performance using various Human-in-the-Loop (HITL) approaches. These approaches utilize diverse technologies and platforms, including Physical Reality (e.g., NASA's Lunar Gateway [32], I-Hab [33]), Virtual Reality (e.g., ESA's Argonaut Moon lander VR demonstration [9], NASA's Deep Space Habitat [1]), Augmented Reality (e.g., NASA's HERA augmented reality study [5], AR-based tapping tasks [6]), and MR platforms (e.g., ISS Cold Atom Lab with MR [27]). However, relatively few studies fully account for actual lunar gravity conditions. Furthermore, even when lunar gravity simulation devices are utilized, their application has been primarily limited to evaluating extravehicular activities (EVAs) or spacesuit performance, as exemplified by NASA's ARGOS project [17].

3 Objective and Methodology

This study aims to conduct a Human-in-the-Loop(HITL) evaluation to comprehensively analyze astronaut task performance and human factors, with the goal of optimizing the operational procedures and internal system design of the LAM. The HITL evaluations are iterative assessments conducted during the design and development process to identify issues related to human systems integration. These evaluations involve user-representative participants performing tasks using representative hardware, software, and procedures [32].

The Human Factors and Behavioral Performance (HFBP) experiments using the LAM-RGS follow a progressive validation process to assess simulator fidelity. Beginning with low-fidelity mockups, the validation extends to mid- and high-fidelity configurations incorporating a 0.16G lunar gravity offloading system at the LUNA Facility in Cologne. This integration pathway allows for the direct application of ergonomics evaluation metrics across simulation stages. The approach provides a low-cost, rapid feedback incremental development strategy in the early phases and generates evidence of human–system compatibility at the final verification stage. These outcomes form a foundation for extending the findings into international design standards, such as NASA-STD-3001 [26].

4 Mixed-Reality Simulator Design

The LAM is designed as a modular system focused on enabling scalable food production and supporting BLSS functions. Structurally, the LAM consists of a rigid cylindrical form approximately 4 meters in diameter and 6 meters in length. The internal layout is broadly divided into two functional zones: the plant cultivation section and the working area (Figure 1). The LAM design used for this HITL evaluation for HFBP can be referenced from the LAM-GTD design (Figure 1) currently under development at DLR.

The LAM-RGS platform comprises three integrated components: a Physical Reality (PR) simulator, a Virtual Reality (VR) simulator, and experimental data acquisition devices. The Mixed Reality (MR) environment combines virtual simulation with physical components to maximize the stimulation of multiple sensory channels, including visual, auditory, tactile, and proprioceptive inputs. This multimodal integration supports a more reliable and operationally representative testing environment.



Figure 2 Concept image of the Lunar Agriculture Module – Reduced Gravity Simulator (LAM-RGS).

4.1 Physical Reality(PR) Simulator

The following two hardware systems constitute the primary environment of the PR setup.

(1) A full-scale physical module of the LAM-RGS will be constructed using aluminum profile structures, not only to reduce experimental costs, but also to ensure realistic simulation quality, offering the added advantage of easy relocation and reassembly.

(2) To simulate the Moon's reduced gravity environment on Earth, the LUNA PUPPETEER [12] (Figure 3) – a gravity offloading system currently under development in collaboration with Space Applications Services as part of the jointly developed Luna Analog Facility [11] by ESA and DLR – will be utilized. The Puppeteer system, developed in collaboration with Space Applications Services. Its primary purpose is to facilitate astronaut and rover training by replicating the Moon's reduced gravitational pull. The development timeline for Puppeteer includes the release of an early version by 2025, with the final, fully refined system expected to be operational by 2026 [10].

4.2 Virtual Reality(VR) simulator

This VR test environment provides an immersive environment capable of simulating detailed IVAs within the LAM. Within the VR environment, key subsystems and equipment or subsystems required for plant cultivation and maintenance are integrated, along with environmental factors such as noise and lighting, thereby supporting a cost-effective and realistic representation of plant growth areas and operational procedures.

4.3 Experimental Data Acquisition Devices

To evaluate human factors and performance under both 1G and 0.16G conditions, data will be collected during the execution of a predefined fundamental movement battery (FMB) and functional task battery (FTB). For this purpose, portable or wearable devices and biosensors will be employed. Additionally, the collected data will be visualized on a dashboard in real-time (Figure 4), providing immediate feedback on key physiological responses, and will also be stored separately for subsequent analysis.

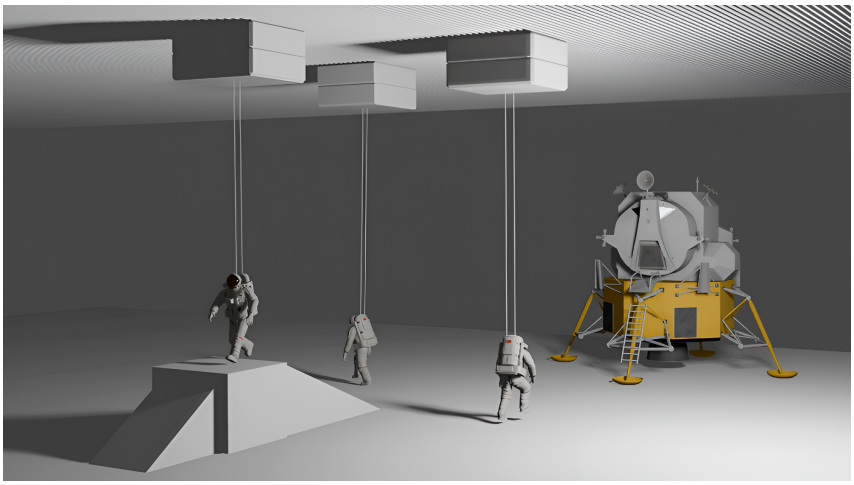

Figure 3 Conceptual image of the LUNA Gravity Offloading System, known as Puppeteer, at the LUNA Facility [12].

5 Research Framework and Implementation Strategy

This section outlines the research framework and implementation strategy developed to investigate the influence of simulated lunar gravity (0.16 G) on human factors and performance during IVA tasks within the prospective LAM. Addressing research questions requires a structured methodology to handle the complex of human-system interaction in reduced gravity simulations. The framework comprises four strategic pillars, which are reflected in the research plan illustrated in Figure 5: (1) Simulator system development and experimental design, (2) Simulator system integration and fidelity assessment, (3) Human factors and performance assessment under terrestrial (1 G) and simulated lunar gravity (0.16G), and (4) data analysis aimed at optimizing internal design of LAM.

5.1 Simulator System Development and Experimental Design

The first pillar focuses on defining operational activities, designing individual LAM-RGS subsystems, and establishing the overarching experimental framework. A low-fidelity simulator prototype – excluding the gravity offloading system – will be constructed and employed in this initial phase to select reliable tasks for the main HFBP experiments and to develop corresponding experimental protocols. This phase also includes the development of data acquisition strategies and the identification and mitigation of potential system limitations that could affect data quality and task performance. These elements will be conducted through an iterative refinement process, structured as a user-centered design loop (Figure 6). The key stages are as follows:

a) **Preliminary Research:** Reviewing relevant documents, manuals, and prior findings from the EDEN-ISS and related projects.
b) **Defining Baseline of Operational Activities for the LAM and LAM-RGS:** Building on EDEN ISS procedures and the LAM-GTD Concept of Operations (CONOPS), this stage establishes the set of LAM operational activities. This includes a systematic classification of tasks encompassing both nominal and off-nominal scenarios – such as logistics handling, plant cultivation, and system maintenance. These baseline activities will serve as the foundation for the development of the FTB within the LAM-RGS framework.

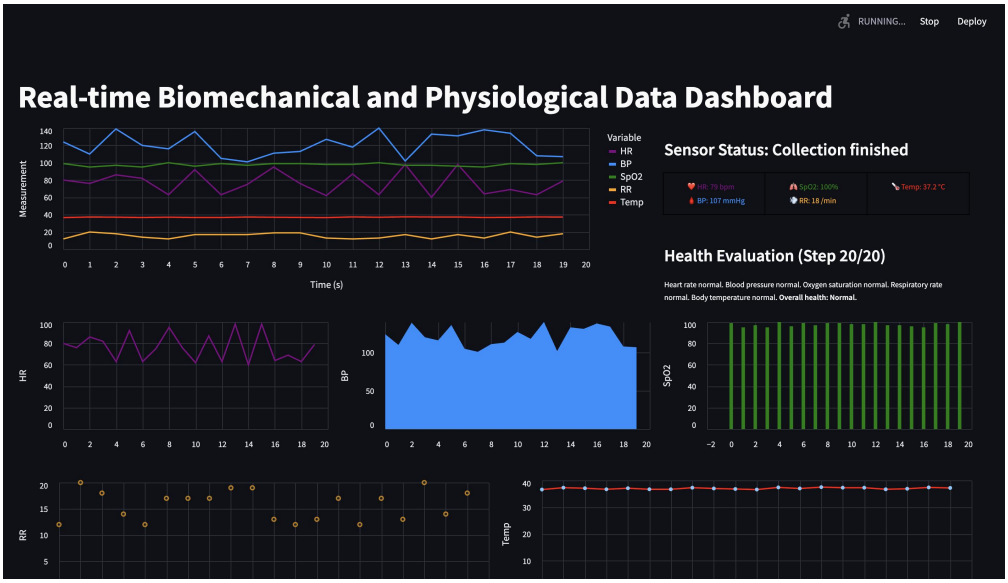

Figure 4 Concept Test of the Data Dashboard for the LAM-RGS Experiment.

c) Initial Functional Task Battery (FTB) and Experimental Protocols Development: At this stage, candidate tasks will be mapped to both VR and PR environments to support the development of a standardized Functional Task Battery (FTB) for LAM-RGS simulations. Potential constraints of the main experiment will be identified through pilot studies and user feedback. Illustrative challenges include the lack of haptic feedback in fully immersive VR environments [30, 18] and the difficulty of accurately replicating fine motor control using gravity offloading systems, as noted in evaluations of NASA's ARGOS platform [13]. Key tasks will then be selected with consideration of these limitations, followed by the development of detailed protocols to ensure simulation reliability and data quality.

(i) Task Mapping for VR- and PR-Based Simulations: Baseline LAM-RGS operational activities will be mapped to VR or PR environments based on task characteristics (e.g., physical logistics to PR for biomechanical assessment). This allocation is based on the Mixed Reality–Virtual Reality Immersion Rating Criteria (MR–VR IRC; as shown in (Table 1)), which classifies tasks according to their degree of VR integration. The rating table was developed with reference to Milgram's Reality–Virtuality Continuum [22]. To address VR's haptic limitations, Level 3 tasks (full VR) will be re-evaluated in pilot studies. For critical tasks highly reliant on haptics, simple physical mock-ups will be created to allow reclassification to Level 2 (mixed reality), or pseudo-haptic techniques will be used for tasks remaining in Level 3. Tasks critically dependent on unresolved haptics will be excluded from the FTB.

(ii) Pilot Study for FTB Selection: All LAM-RGS operational activities will be tested with users, applying the evaluation criteria outlined in Table 2. Through quantitative scoring and analysis of task-specific characteristics, this process aims to finalize the selection of activities to be included in the FTB used in the LAM-RGS.

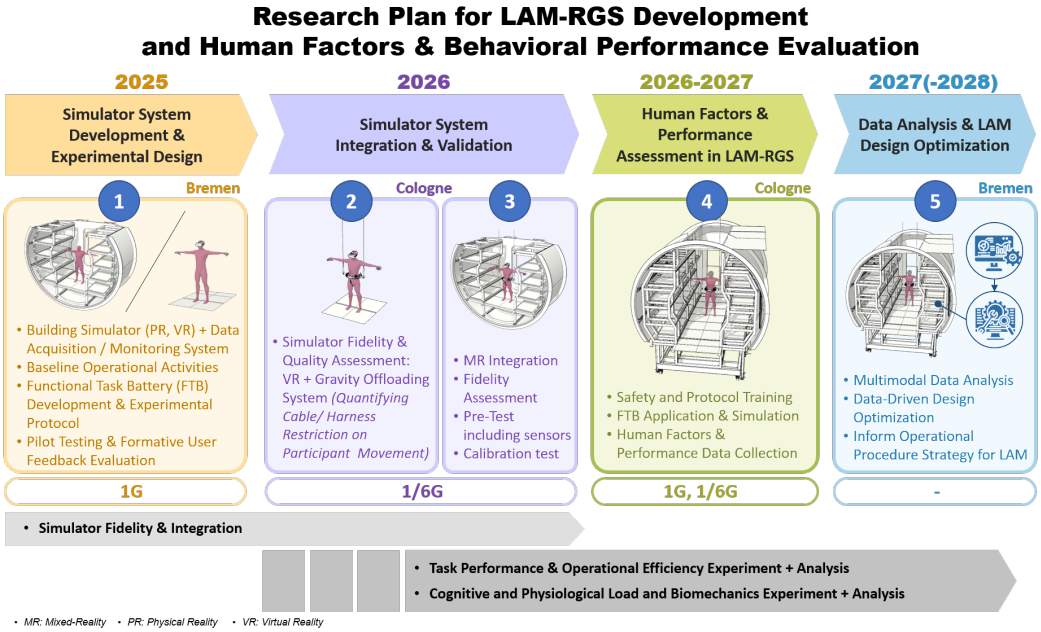

Figure 5 Research Plan for LAM-RGS Development and Human Factors and Behavioral Performance Evaluation.

To address the limitations of VR-based simulation – particularly the lack of haptic feedback – each task is rated for its level of haptic dependency. Initial simulation quality assessments incorporate proxy indicators for this dependency and include participants' subjective evaluations of realism, control difficulty, and sensory discomfort.

In addition, given the inherent limitations of the current gravity offloading system – particularly in replicating fine motor control and joint-specific kinematics – this pilot study includes monitoring of body segment engagement across activities to assess fine motor skill dependency and system-induced limitations. Consequently, this study is structured to address current technological limitations by prioritizing the assessment of gross motor functions – such as overall body coordination, postural stability, workspace utilization, and movement efficiency – over fine joint-level measurements.

(iii) **Key Tasks Selection for FTB:** User feedback data will yield quantitative scores to prioritize activities for the FTB.

(iv) **Detailed Experimental Protocols Development:** Each FTB task follows a structured protocol outlining procedural steps, tool setup, performance criteria (e.g., time, accuracy, error types), and pass/fail conditions. It also defines environmental settings and includes risk mitigation measures to ensure safety and data reliability.

d) **First-Stage Expert Review:** Protocols will be reviewed by experts to ensure validity and relevance, followed by revisions.

e) **Second-Stage Validation:** Each FTB task will have a documented protocol detailing procedures, tools, performance criteria, and risk mitigation.

f) **Final Version Approval for the Main Experiment:** Pre-tested protocols meeting safety and operational relevance criteria will be approved for 0.16G trials.

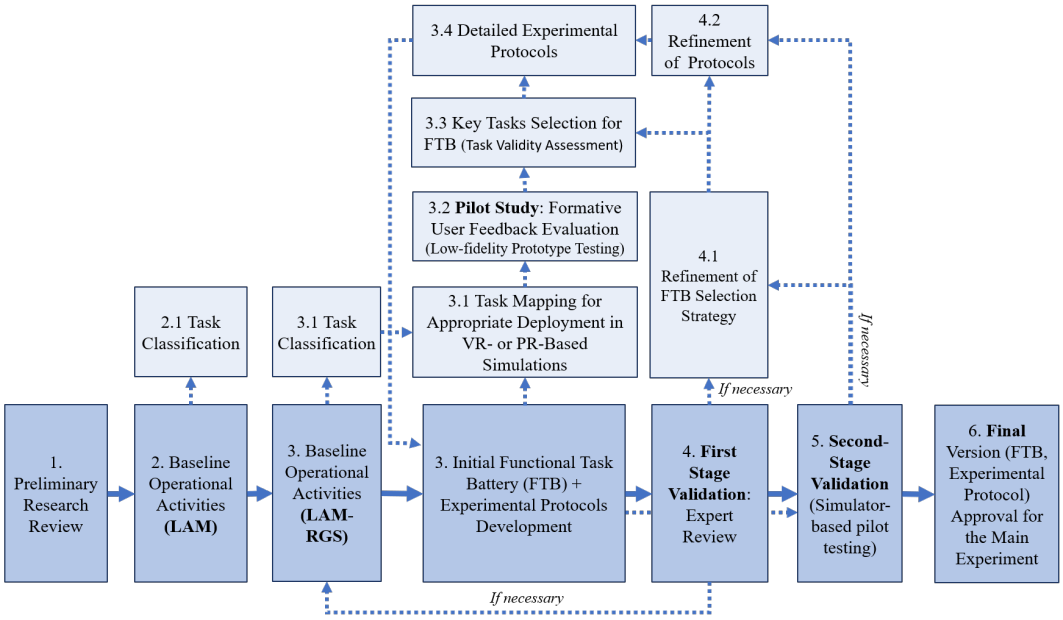

Figure 6 Functional Task Battery (FTB) and Experimental Protocol Development Process for the Main Experiment of LAM-RGS.

5.2 Simulator System Integration and Fidelity Assessment

This phase aims to validate and refine the low-fidelity MR modules, FTB, and experimental protocol to develop a mid-to-high fidelity LAM-RGS, ensuring consistent task execution and reliable multimodal data collection. As shown in Figure 5, this pillar has two validation stages: VR-Puppeteer Integration Test and MR-Puppeteer Integration Test. These steps are assigned not only to achieve seamless and rigorous system integration, but also to evaluate the fidelity and functional limitations of the gravity offloading system itself. This dual objective is critical, as previous EVA and spacesuit simulation studies utilizing gravity offloading technologies have shown that harnesses and suspension cables may either restrict natural motion or introduce artificial movement artifacts [13]. Therefore, minimizing such constraints is essential to preserving the validity of movement performance data in simulated partial gravity environments.

a) **VR–Puppeteer Integration Test:** The LUNA facility's gravity offload system will be integrated with a Virtual Reality (VR) environment for preliminary testing. This test aims to evaluate potential movement and task execution constraints imposed by the system's cable and harness on participants. A Fundamental Movement Battery (FMB), adapted from NASA's ARGOS project [13], will be employed for this assessment. The FMB comprises representative full-body tasks, including ambulation and gait assessment, kneeling and recovery, prone-to-stand transitions, object retrieval, target reaching, and torso rotation.

   Data from evaluating the harness's impact on individual FMB movements will serve two key functions. Firstly, it will act as a diagnostic tool to identify and manage potential data distortions in similar movements during the subsequent FTB execution, guiding decisions on data exclusion or analytical weighting. Secondly, this dataset will be used to quantitatively assess the influence of the Puppeteer offloading system on fundamental anthropometric and kinematic parameters (e.g., joint angles, range of motion) under simulated 0.16G conditions. This evaluation will establish a system fidelity baseline and aid in interpreting biomechanical data from the main experimental phase.

Table 1 Simulation Modality Levels for Task Evaluation in Mixed-Reality Environments.

Level	Type	Description	Examples of Expected Task
Level 1	Non-VR (Physical Reality Only)	No VR implementation required. 100% physically executable. No VR interaction	Basic button/switch operation tests, Simple ergonomic evaluations, Hardware usability tests, Simple physical item movement.
Level 2	Partial-VR (Mixed physical+virtual interaction)	PR-based with key virtual subsystems or elements. PR–VR interaction with PR essential for tasks. VR Dependence (Task Time/Elements): 10-90%<	Accessibility, reachability & posture check during VR interaction, Supply Management, Workspace and layout Design Verification across VR tasks, Repairs, Cleaning
Level 3	Full-VR (High Immersion)	Almost entirely VR-based experiment, excluding minimal PR. Suitable for evaluating/training complex/hazardous scenarios hard to replicate physically. Physical Execution: Impractical/Impossible. VR Dependence (Task Time/Elements): >90%	Simulation of complex operational tasks, Emergency Response(Fire, leak), Complex system diagnostics, System maintenance/monitoring, Plant growth, Operating robotic arm

This stage also incorporates verification and adjustments to ensure consistent harness conditions across 1G and 0.16G environments. This consistency is critical for reliable relative comparisons of human factors and performance metrics in later research stages. Any identified inconsistencies or suboptimal harness fit will be addressed through corrective actions, such as adjustments in harness placement.

b) MR–Puppeteer Integration Test: The complete simulator configuration (MR simulator, Puppeteer, data acquisition components) will undergo final validation. This focuses on verifying system interoperability and synchronization, iteratively refining fidelity and usability using quantitative metrics and qualitative user input under 1G and 0.16G conditions. Despite efforts to minimize fine motor skill dependency, the offloading system is expected to have limitations in fully replicating lunar conditions for all FTB fine motor activities. This final validation aims to identify remaining limitations and inform necessary adjustments to the research strategy.

5.3 Human Factors Assessment Under 1G and Simulated 0.16G Conditions

The third pillar constitutes the main experimental phase of the study and investigates the effects of gravitational loading on task performance, cognitive and physiological workload, and biomechanics. These factors will be measured during the execution of the FTB under both Earth gravity (1G) and simulated lunar gravity ($\sim$ 0.16G). The primary goal under 0.16G is to assess absolute changes in human factors and performance, while the 1G condition

Table 2 Evaluation Criteria for Functional Task Battery selection.

Evaluation Domain	Description
Task Completion Time	Indicator of task complexity and procedural efficiency.
Task Stability	Captures errors and balance instability events.
Biomechanical Load	Frequency of gravity-sensitive postures; rated for fine/gross motor dependency (High/Med/Low).
Workspace Usage	Extent of movement and identification of key tactile interaction points.
Subjective Workload	Mental, physical, and temporal demands (NASA-TLX / DLR-WAT).
Simulation Acceptability	Quality and realism ratings via Likert scales and user interviews.

serves as a baseline for evaluating relative differences in cognitive load, musculoskeletal strain, task efficiency, and ergonomic strategies across gravity environments. Quantitative and qualitative data will be collected across the following key domains as follows.

a) Task Performance and Operational Efficiency

(i) Objective Performance Metrics: Data will include task completion time, error rates (categorized by type and severity), success/failure rates, task-specific accuracy, and behavior-based indicators such as the frequency of specific postures, idle time, or repetitive motions.

(ii) Subjective Workload and Usability Measures: Participants will complete validated post-task surveys (e.g., NASA-TLX [24] or DLR-WAT [2]), and the System Usability Scale (SUS). These will measure perceived mental demand, physical effort, time pressure, and frustration, providing insight into how reduced gravity affects perceived workload and usability.

b) Cognitive, Physiological, and Biomechanical Data Collection

(i) Cognitive Assessment: Electroencephalography (EEG) will be used to monitor cognitive load, attention shifts, and mental fatigue. Analyses will focus on frequency bands (e.g., theta, alpha) associated with task engagement and working memory.

(ii) Physiological Monitoring: Real-time physiological parameters will be collected, including heart rate, heart rate variability (HRV), estimated CO_2 metabolic expenditure, and muscle activation via surface electromyography (EMG). These data will be used to assess energy expenditure, stress responses, and localized muscle fatigue during task performance.

(iii) Biomechanical and Anthropometric Analysis: A motion capture system for human body posture recognition will be used to track macroscopic kinematic variables such as joint angles (at segment level), segmental velocities, movement trajectories, postural stability, and workspace utilization. Given the limitations of simulating fine motor control under partial gravity conditions, emphasis is placed on whole-body coordination patterns and gross movement dynamics, which serve as more robust indicators of functional performance and ergonomic risk in this context. These measures will support the identification of compensatory or altered movement strategies used to maintain task stability in reduced gravity.

5.4 Multimodal Data Analysis and LAM Internal System Design Optimization

The final pillar of the framework integrates and analyzes diverse datasets to derive evidence-based recommendations for LAM design and operational concepts.

a) Cross-Environment Comparative Analysis The objective of this analysis is to compare and analyze differences in task performance and cognitive/physiological responses when identical tasks are performed across two different environments. The focus is on variations in execution strategies, performance outcomes (e.g., speed, accuracy, error rates), cognitive load, physiological, and biomechanical responses. Statistical methods such as ANOVA, t-tests, or nonparametric equivalents will be used to compare.

b) Multimodal Data Integration To investigate both short-term responses and long-term human adaptation under simulated lunar gravity, this study adopts a multimodal analytical framework that integrates temporally synchronized data streams of HFBP. With the analytical framework still in the planning stage, the study is exploring advanced multivariate statistical techniques designed to address the anticipated complexity and high dimensionality of the data. (Table 3) outlines the potential domains for comprehensive evaluation through integrated, correlation-based analysis.

Table 3 Potential Domains for Evaluation and Multimodal Data Integration in LAM-RGS.

Domain	Potential Data Integration	Application Objective
Human-System Interaction Optimization	Behavioral performance, biomechanical data	Design guidelines for safe internal layout and workspace configuration.
Task Efficiency Improvement	Cognitive workload, physiological signals	Development of efficient task protocols & OPS under lunar gravity.
Ergonomic Risk Management	Posture analysis, motion patterns, EMG, cognitive load	Prediction of ergonomic risks and injury prevention strategies.
Training Optimization and Metrics Development	Performance scores, cognitive and physiological metrics	Mission capability assessment and training proficiency criteria.
Adaptation Pattern Identification	Performance scores, physiological signals cognitive workload, biomechanical data	Understanding long-term behavioral/cognitive adaptation in MR and lunar gravity.

Machine learning techniques, such as clustering and pattern recognition, may be employed to identify complex behavioral profiles or fatigue-related trends. However, the primary analytical emphasis remains on interpretable statistical methods that align with human factors and ergonomic research objectives.

c) Human Factors Engineering for LAM Design Improvements Based on integrated data analysis, this study offers evidence-based design recommendations to optimize the LAM's internal systems. Key suggestions include refining workspace layout, adjusting work surface heights, and repositioning controls and interfaces to reduce physical and cognitive workload, lower error risks, and enhance user safety and operational efficiency. These findings will enrich the broader human factors knowledge base for lunar surface operations and inform standardized design guidelines for critical off-world infrastructures, such as habitats and laboratories.

6 Conclusion and Potential Applications of the Simulator

This paper has presented the LAM-RGS, an experimental platform currently under development at DLR to address a critical knowledge gap in human factors and performance research for IVAs within a lunar BLSS, specifically the LAM. The simulator integrates a MR environment, experimental data acquisition systems, and a dynamic gravity offload system (Puppeteer) to enable mid- to high-fidelity evaluation of astronaut behavior and performance under simulated lunar gravity (0.16G).

By moving beyond traditional EVA and habitat studies, this research targets the underexplored domain of IVA-related agriculture and logistics tasks in partial gravity. The LAM-RGS facilitates comprehensive multimodal data collection – encompassing objective and subjective task performance, efficiency, and workload under both terrestrial (1G) and simulated lunar (0.16G) conditions. The anticipated outcomes include data-driven insights into human performance limitations, adaptation strategies, cognitive and physiological workload, and biomechanical responses associated with performing essential tasks in a partial gravity environment. These findings are expected to inform evidence-based design recommendations for optimizing internal layout, ergonomic interfaces, and operational procedures within the LAM. Ultimately, this study aims to contribute substantially to the human factors knowledge base required for long-duration lunar missions.

The LAM-RGS platform is envisioned as a versatile and mid-to high-fidelity testbed with multiple potential applications. The simulator may support iterative design validation of BLSS systems, astronaut training in lunar-specific IVAs, and refinement of nominal and off-nominal operational procedures. Furthermore, the platform enables advanced investigations in human–system integration, ergonomic assessment, and technology evaluation under partial gravity conditions relevant to lunar surface operations.

In conclusion, future research will focus on implementing and refining the proposed framework, completing the development of the LAM-RGS simulator by 2025, and executing the planned experimental campaigns. This work is expected to advance our understanding of human performance and system interaction in reduced gravity and provide the methodological foundation necessary to enable sustainable human exploration and habitation on the Moon.

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Integrating Human-In-The-Loop AI to Tackle Space Communication Delay Challenges

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Abstract

Deep space missions face significant communication delays that disrupt both operational workflows and psychological support for crew members. Unlike low Earth orbit operations, delays ranging from several minutes to nearly an hour make real-time communication with mission control infeasible, forcing crews to act with greater independence under uncertain conditions. This position paper examines how human-in-the-loop AI, digital twins, and edge AI can be integrated to mitigate these delays while maintaining astronaut autonomy and engagement. We argue that human-in-the-loop AI enables decision-making processes that are responsive to local context while remaining adaptable to changing mission demands. Digital twins offer real-time simulation and predictive modelling capabilities, allowing astronauts to explore options and troubleshoot without waiting for ground input. Edge AI brings computation closer to data sources, enabling low-latency inference onboard spacecraft for time-critical decisions. These ideas are explored through two use cases: using deepfakes to support emotionally resonant communication with loved ones, and applying visual-language models for onboard fault diagnosis and adaptive task replanning. We conclude with reflections on system design challenges under constrained and high-stakes conditions.

2012 ACM Subject Classification Human-centered computing

Keywords and phrases Human-in-the-loop AI, communication delays, human spaceflight

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1 Introduction

Human spaceflight and exploration have seen a renewed interest from government space agencies and industry. While Low Earth Orbit (LEO) has been the main focus for recent human spaceflight activities, the new Space Race aims to place humans in lunar orbit, Mars, and the lunar surface for long-term establishment. These targets require advanced technical capabilities. The Artemis missions will involve spacesuits with numerous sensors for transmitting multi-modal data, for visual sensing, life support, and fault detection [16]. The Gateway space station will support human missions ranging from 30 to 90 days and autonomous operations while not staffed [32]. But no matter the nature and place of the spaceflight operation, there is a significant capability that must be met: the need for **robust communication**. This includes communications between the Mission Control Centre (MCC) and astronauts, as well as communications between astronauts with local spacecraft systems such as robotic arms.


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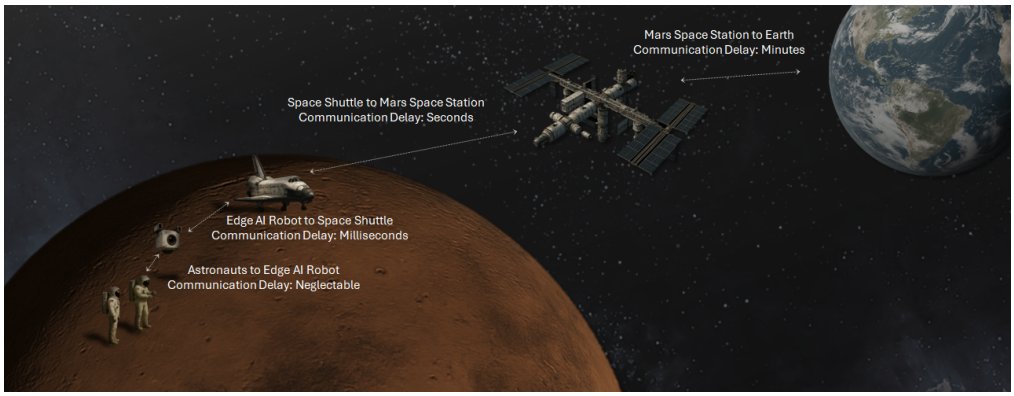

Figure 1 The challenge of communication delay in space operations, as illustrated by a hypothetical mission to Mars.

There exist various challenges to effective communications in space, both environmental and technical [47]. The most prominent challenge in maintaining communications in the space is signal delay. Signals, (including commands, telemetry, voice, and video), can take minutes to hours of travel between MCC and distant spacecraft via the Deep Space Network (DSN). Significant communication delays in deep-space missions pose major challenges for real-time data exchange and operational efficiency (Fig. 1). As a spacecraft moves farther from Earth, these delays increase; for example, after 90 and 480 days of travel (covering 0.4 and 2.7 Astronomical Units), one-way signal delays can reach 4 and 22 minutes, respectively [43][64].

Dealing with **communication delays** is very important in the context of human spaceflight, especially for longer-term missions further from Earth. Research performed on the ISS has shown that communication delays of 50 seconds, which correspond to delays that could be present in deep space missions, can negatively affect the crew's behaviour, leading to task performance degradation, stress, and deteriorating mood [44]. Communication delays can be challenging not only for astronauts, but for the MCC as well. This has been showcased in mission analog studies, where increased communication delays did affect the MCC task performance, as well as unavoidably increased their workload, elevated stress levels, and led to task failure [35][21]. These studies mention astronaut compliance issues as a result of communication delays, leading to a lack of command acknowledgement. Some other spaceflight concerns related to communication delays are impacts on team cohesion and impacts on emergent medical assistance from the MCC [57].

These delays necessitate autonomous and adaptive solutions to maintain mission effectiveness while ensuring human oversight and decision-making remain integral [64]. Indeed, the outcome of some studies involving real astronauts [44] suggested "increase crew autonomy" and "reduce back-and-forth communications" as ways to address communication delays and the resulting performance degradation and related stress. One astronaut in the study also stated: "I think if we fly to Mars we are going to have a spaceship that is more autonomous than the ISS. So you don't have as much low-level comm. with the ground on each of the steps of the procedures". When asked what type of tools would help with communication delays, the astronauts stated the need for a "recording-tool" and "text or video-based communications" as well as that "the AMO [autonomous mission operations] software" helps increase their autonomy. It is evident that increased autonomy could mitigate some effects of communication delays, by reducing the number of times the communication takes place. To tackle this challenge, in this paper, we discuss how AI could be leveraged to provide more autonomy

to the crew. AI has been explored before as a prominent tool to solve challenges in human spaceflight [53], but in this paper, we focus on the usage of AI and its potential to address communication delays in human spaceflight. Recent advances in **human-in-the-loop AI** offer promising ways to bridge these communication gaps by balancing automation with human expertise, including designs that put humans in decision-making processes. Rather than fully autonomous systems making decisions in isolation, AI enables astronauts and mission controllers to guide, adapt, and refine AI-driven processes in real time, even under significant latency constraints. This hybrid approach enhances mission resilience, allowing crews to interact with AI systems that learn from human feedback and adjust to evolving mission needs.

Communications between the MCC and crew take place for various purposes: some important purposes include task planning, system monitoring and fault management, astronaut health monitoring, and communication with family members. Each type of communication can have different modalities, such as voice commands, video feeds, log transcripts, monitoring signals, etc. This paper focuses on categorising communications into two types: *task-oriented* and *social-oriented*. Task-oriented communication focuses on operational efficiency, such as teleoperating robotic arms onboard. Social-oriented communication, on the other hand, supports crew psychological well-being, as astronauts seek connection with people on Earth, especially family members. Solutions like AI-driven Delay-Tolerant Networks [3][13].and Enhanced Communication Protocols [60][26] incorporate human-in-the-loop AI to ensure critical tasks are performed with precision, even in delayed-response environments. **Space Braiding** [51] is a recent initiative aimed at fostering meaningful remote interactions by leveraging AI while keeping human intent at the core of communication design.

In the following sections, we first review the literature on the use of AI in space in general and communication delays in particular, examining their potential and limitations in addressing this critical challenge for deep space exploration. Specifically, we examine the applicability of Digital Twins and Edge AI in addressing space communication delays. Next, we present our proposed solutions through two use cases: one explores task-oriented communication, applying the concept of backtracking to robotic arm operations, while the other focuses on social-oriented communication, investigating the potential benefits of deepfakes in casual conversations with social contacts on Earth.

2 Literature Review

2.1 AI in Space

The uses of AI in most aspects of spaceflight have been showcased and described before. A recent literature review categorised different AI methodologies and algorithms, and matched them with technical problems in satellite engineering where they could provide a solution [61]. This review focused more on technical aspects of satellite engineering, rather than operations and issues in human spaceflight. The review by Furano et al. focused on AI applications and challenges for embedded systems in space [33]. The potential of AI in facilitating mission operations and space exploration is described by Russo et al. [72]. AI has also been introduced in the phases of spacecraft design, with an example being an expert system as an assistant in the process of engineering design [9].

In the field of space communications, Fontanesi et al. have presented a very detailed review of the application of AI in communication issues [28]. They categorised different AI methodologies, described common hardware and task-related problems in satellite communications, mentioned the state-of-the-art in AI to solve these problems, and provided

other relevant reviews. But even this detailed review did not mention the challenges and opportunities for AI in mitigating communication delays, or the implications in human spaceflight.

AI has also been proposed in the context of addressing challenges in human spaceflight. Some notable applications include deploying autonomous AI agents for task planning and scheduling, onboard system fault detection and management, and AI-powered robotic assistants onboard the ISS. A prominent example is the NASA Autonomous Systems and Operations project (ASO) that deployed AI methods for increasing crew autonomy and automating operations both in deep space mission analogs and onboard the ISS [29]. Finally, various robotic assistants have been deployed onboard the ISS to help astronauts with everyday tasks, such as Robonaut2 [22], SPHERES [78], Astrobee [12], Int-Ball [58] and Int-Ball2 [39]. Again, these efforts of introducing AI and increased autonomy onboard the ISS did not address communication delay issues.

Due to the sensitive and high-stakes nature of space missions, responsible AI design is essential [23]. Graham and Thangavel [36] argue that while AI offers significant advantages for space applications, its deployment presents unique risks that require tailored responsible AI frameworks. Balancing the prevention of harm with mechanisms for accountability and remediation is necessary. Oche et al. [61] emphasised the importance of responsible AI considerations when applied to key areas of space missions, including spacecraft health monitoring, remote sensing, satellite communications, and robotic autonomous systems.

2.2 AI for Space Communication Delays

One primary approach to addressing communication delays involves integrating AI into spacecraft systems to enable autonomous decision-making. Since real-time communication over vast interplanetary distances is impractical, AI allows spacecraft to perform critical functions independently. For instance, AI algorithms can autonomously process scientific data, adjust mission parameters, and manage unexpected events, ensuring mission continuity despite communication lags [8]. NASA and the German Aerospace Center (DLR) have been developing intelligent AI assistants, such as the Mars Exploration Telemetry-Driven Information System (METIS), to monitor spacecraft systems, detect anomalies, and support astronaut autonomy by reducing reliance on mission control [8]. AI is also being leveraged to develop advanced communication protocols that can dynamically adapt to space environments. AI-driven systems can optimise data transmission by selecting underutilised frequency bands, minimising interference, and maximizing available bandwidth. This adaptability is crucial for maintaining robust communication links despite challenges such as space weather fluctuations and resource constraints [29]. NASA's cognitive radio technology exemplifies this approach, using AI to make real-time decisions about spectrum use and improving resilience against signal degradation [56].

Delay-Tolerant Networking (DTN) is a networking paradigm designed to function effectively over long distances and intermittent connections, making it particularly suited for space missions [3]. AI-enhanced DTN protocols have been developed to improve routing efficiency and data delivery in these challenging conditions. For example, AI-based routing mechanisms can predict network disruptions and dynamically adjust data paths, increasing the reliability of space communications [13]. ESA and NASA are actively researching AI-augmented DTN models to enhance interplanetary communication, ensuring stable data transmission despite extreme delays [3].

In addition to technical advances, innovative communication tools such as Space Braiding have been introduced to mitigate the psychological and operational impacts of communication delays on astronauts. Space Braiding creates the illusion of real-time conversation by intelligently managing pre-recorded message exchanges, thereby preserving a natural dialogue flow despite inherent delays [70]. Recent studies funded by ESA have demonstrated the effectiveness of Space Braiding in improving crew well-being, enabling effective problem-solving under high-latency conditions, and facilitating psychological support through therapist-guided sessions during simulated Mars missions [51].

AI's role extends to optimising satellite communication networks by analysing vast amounts of operational data and predicting potential issues such as signal interference and bandwidth allocation. For example, AI systems can dynamically adjust satellite parameters to maintain optimal communication links, thereby reducing latency and enhancing data throughput [28]. Research has highlighted the potential of AI in improving the efficiency of satellite communication networks by addressing challenges such as resource management and network control [45]. Additionally, integration with Augmented Reality (AR) tools can enable astronauts to interact with communication data in real time, further enhancing operational efficiency [8].

2.3 Human-in-the-loop AI for Space Missions

Unlike fully autonomous systems, which operate without human intervention, human-in-the-loop AI combines human intuition, expertise, and situational awareness with AI's computational capabilities. This approach ensures that mission-critical decisions remain aligned with human intent while benefiting from AI's ability to process vast amounts of data and make rapid adjustments.

One concrete example of this approach is AI-assisted spacecraft navigation, as seen in NASA's autonomous navigation systems. Traditional deep-space navigation relies heavily on Earth-based tracking and ground control for trajectory adjustments. However, long communication delays make immediate course corrections impractical. NASA's AutoNav system, originally deployed on the Deep Space 1 probe and later refined for Mars rovers like Perseverance, enables spacecraft to autonomously adjust their paths. Despite its autonomy, AutoNav remains under human oversight; mission planners set high-level goals, and the AI executes navigation while continuously sending updates back to Earth for validation [11][55].

A similar hybrid model is applied in AI-supported fault detection and recovery, an essential function in spacecraft operations where failures can have catastrophic consequences. ESA has been testing AI-based fault detection through OPS-SAT, a mission that allows ground controllers to interact with and fine-tune AI decisions when anomalies arise [25] [30]. Meanwhile, NASA's R5 Valkyrie, a humanoid robot designed for deep-space exploration, is capable of performing routine maintenance tasks on spacecraft. However, rather than operating in full autonomy, Valkyrie allows astronauts and mission controllers to modify its actions through isolation of remote commands [69].

Medical decision-making in space is another domain where human-in-the-loop AI proves invaluable. Long-duration missions require astronauts to manage their own healthcare without immediate guidance from Earth [59]. To address this, NASA has developed the Clinical Decision Support System (CDSS), which assists astronauts by analysing physiological data, identifying potential health risks, and recommending treatments [71]. However, instead of relying entirely on AI-generated diagnoses, astronauts remain actively involved by providing symptom inputs and cross-checking AI-generated recommendations against available medical guidelines and consultations with ground-based physicians.

Beyond operational efficiency, human-in-the-loop AI is also being explored for maintaining crew psychological well-being during long-duration missions. The Space Braiding initiative [60][26], for instance, leverages AI to filter and adapt asynchronous messages from family members, ensuring that astronauts receive meaningful and supportive communication even under delayed conditions.

By integrating human oversight into AI-driven processes, deep-space missions can retain flexibility, enhance operational safety, and preserve the psychological well-being of astronauts despite communication delays.

2.4 Digital Twins and Space Communication Delays

Digital Twins (DTs) offer a powerful solution by enabling real-time simulation, predictive modelling, and autonomous decision-making. Virtual replicas of spacecraft, planetary rovers, or habitats allow engineers and astronauts to anticipate challenges and reduce reliance on Earth-based commands [52]. One of the primary advantages of DTs is their ability to support local decision-making and autonomy. With long signal travel times, spacecraft cannot always wait for instructions from mission control. Instead, onboard DTs can simulate potential outcomes of various actions in real time, enabling spacecraft or planetary rovers to make informed decisions without immediate human input. This capability enhances mission efficiency and reduces risks associated with delays [68].

DTs also play a crucial role in predictive maintenance and fault detection [79]. By continuously monitoring spacecraft components and systems, they can identify signs of wear or potential failures before they become critical. Engineers can then test repair strategies in a virtual environment before executing them in space, minimizing the need for extensive back-and-forth communication with Earth [52].

In addition to supporting real-time operations, DTs enhance training and simulations on Earth. Mission control teams can interact with highly detailed virtual replicas of spacecraft or space habitats, allowing them to test responses to unforeseen conditions without direct input from the remote system. Astronauts can also use DTs to rehearse tasks before performing them in space, improving their success rate and reducing the risk of errors[67].

Another advantage is optimised data compression and synchronisation. Instead of transmitting vast amounts of raw data back to Earth, DTs can preprocess and filter critical information, significantly reducing bandwidth requirements. Spacecraft can also update themselves using pre-programmed decision models within their DT framework, allowing them to function more independently [74].

Looking ahead, human-AI collaboration in space habitats will be an essential aspect of future missions. Mars bases or lunar settlements could integrate DTs to manage life-support systems, optimise resource utilization, and respond to emergencies autonomously [37]. By reducing dependence on real-time Earth intervention, these AI-driven systems will enable sustainable long-term human presence in space.

Several space agencies and private companies are already leveraging DTs to mitigate communication delays and enhance autonomy in space missions. In NASA's Artemis Program, DTs are being developed to autonomously monitor lunar spacecraft, habitats, and the planned Lunar Gateway station, enabling predictive maintenance and operational efficiency. For NASA's Mars Rover missions, the Perseverance Rover's Earth-based DT allows engineers to simulate commands and troubleshoot issues remotely before execution, minimising delays caused by long communication times.

Similarly, Digital Twin Earths (DTEs) are high-fidelity models that predict environmental changes in Earth's atmosphere, reducing the need for continuous real-time satellite data transmission [7]. Similarly, Boeing's Digital Twin of the CST-100 Starliner spacecraft supports pre-emptive testing of navigation, life support, and propulsion systems, ensuring safer and more reliable space travel [18].

Lockheed Martin's Orion spacecraft also benefits from a DT, which aids in testing flight scenarios and emergency procedures, enhancing mission preparedness [66]. Meanwhile, SpaceX Starship employs AI-driven DTs, allowing the spacecraft to autonomously detect and address structural or operational issues during deep-space missions [4]. These advances collectively contribute to greater autonomy, efficiency, and resilience in space exploration.

2.5 Edge AI and Space Communication Latency

The term Edge AI is inspired by edge computing, the process of moving the computational and storage systems of a computer network closer to the "edge", i.e. the point of deployment where the data come from. Similarly, Edge AI refers to the deployment of AI models closer to the source of data collection, usually as part of an embedded computer [34]. This solution can mitigate communication delays, as data transferring between the user, storage, and computation system is significantly reduced.

This idea is not new, and it is typically associated with Internet-of-Things (IOT) networks. Due to the large amounts of data generated by each device, different data types collected, limited communication bandwidth, varying processing capabilities of each device, and variable power demands, communication between devices can have increased latency. A mitigation technique example is the usage of AI algorithms as a routing task agent in systems according to each device's task request number, power consumption, available battery and other resources [6]. An extensive review paper on ways of mitigating latency, arising both from computational constraints and communication constraints is presented by Shi et al [75]. In the review, the mitigation methods are categorised into methods for communication-efficient Edge AI systems that optimise the AI algorithms, and methods that optimise the data processing systems and principles.

Since satellites are remote systems with embedded processing capabilities, Edge AI can offer a promising solution for the communication delay problem. In a similar way with ground communications, Edge AI could be used to determine what data types need to be prioritised for transmission, how they could be compressed/optimised, how to plan and schedule link operations, and how to take advantage of novel computing architectures and processing capabilities in space. The increased launches and usage of satellite constellations has made this need more relevant. A recent paper outlines the processing and memory requirements that modern onboard AI/ML systems must meet to enable edge computing and AI integration in satellite communications. It also discusses the technical challenges in satellite communications that these systems could help address [62][40]. Leveraging AI and edge computing has been proposed to enable scheduling optimisation between ground stations and satellites, in the context of a satellite constellation network [83]. An Edge AI architecture for satellite constellations in LEO can also help constellations make AI inference onboard, rather than downlinking the data to a ground server that runs an inference algorithm, then having the inference result uplinked and distributed to end-users through the constellation [84].

Our position in this paper is that Edge AI could be leveraged more for communications in human spaceflight. The simplest way this can happen is by exploiting the constellation communication results and paradigms mentioned above: the space station can be simultan-

eously another computation/communication module in the constellation, the edge where data is collected, and the end user. A recent user case of interest is space crew health assessment. Edge AI could be used to gather health and biometric data from the crew and perform inference on each crewmember's health condition. Training for such a system could be performed by medical data on Earth, and the inference system could be performed in space [82] through a constellation network or other high-performing embedded processors and Edge TPUs [46]. Since Edge processors would offload computing data, medical diagnosis can be performed using many different data types, such as EEG and other biosensing signals, camera images, voice commands, and text data. Data transformation, processing, and AI inference could be performed either onboard or using a constellation, providing a first medical state report, minimising the need to contact the MCC, and providing additional information when contacted.

3 User Cases

To showcase the applicability of AI as a delay-mitigation measure, we discuss two hypothetical human spaceflight user cases. The first user case addresses social-based communications, and the second task-based communications. We propose the usage of AI agents based on similar scenarios in terrestrial applications.

3.1 User Case 1: Deepfakes for Social-oriented Communications in Deep Space Exploration

While initial studies on Space Braiding [51] funded by agencies such as the UKSA, ESA and NASA highlight its potential, key areas require more empirical validation to assess its long-term impact on communication efficiency, team cohesion for various group sizes, and astronaut well-being. As a text-based tool, Space Braiding may be well-suited for task-oriented communication but less effective for social interactions, such as conversations with family and friends, where voice and video communication are more natural and emotionally engaging. Research into more accessible interfaces that support multimodal communication could help address this limitation. A viable alternative can be deepfakes.

Deepfakes are highly realistic digital creations that utilise AI, complex algorithms, and advanced data processing techniques [65]. These technologies enable the seamless integration of an individual's real-world visual and auditory characteristics into carefully crafted artificial environments, producing media that appear strikingly authentic [80]. Combined with generative AI techniques such as conversation agents and human behaviour synthesis, deepfakes enable the creation of believable virtual agents that can conduct supportive conversations. Despite concerns about their potential for manipulation, deepfakes are not inherently deceptive or malicious [38]. In fact, they can be used positively in cultural applications, entertainment, and even psychological well-being [15].

Recent research has explored how people emotionally engage with deepfakes, even when they are fully aware of their artificial nature. Using neuropsychological methods, Eiserbeck et al. [24] examined how recognising AI-generated faces influences emotional processing. Their findings suggest that participants perceived smiling faces labelled as "fake" as less positive and reacted to them more slowly. However, their responses to angry faces were consistent, regardless of whether the faces were real or artificial. Soto-Sanfiel et al. [77] investigated human interactions with deepfakes across different genres, such as celebrities, advertising, and politics. Their study revealed that immersive narratives and familiarity with the content can enhance engagement and enjoyment.

Building on this potential, we propose utilising deepfakes to address the psychological needs of spacecraft crews by enabling emotional connections with their loved ones during long missions. Family members and friends can continuously record videos of daily activities, which will be stored in a database. These recordings will serve as training data for AI models to generate deepfake avatars that accurately replicate their appearances, voices, and behaviours. When a crew member wishes to interact with a family member, the system will retrieve relevant content and render it as a fully immersive 3D simulation with advanced re-enactment techniques [19]. By integrating these AI-generated representations into a virtual environment and leveraging the power of Edge AI, the system can create a lifelike and emotionally engaging experience, helping astronauts feel more connected to their families despite the vast physical distance, thereby sustaining their mental health.

However, the ethical implications of using deepfakes in this context must be carefully considered [50][20]. Consent is a critical factor – family members and friends must have full control over how their likenesses are used and be able to withdraw permission at any time. Additionally, prolonged interaction with AI-generated representations may blur the boundaries between reality and simulation [38], potentially affecting astronauts' emotional well-being upon returning to Earth. There is also the risk of unintended psychological effects, such as over-reliance on artificial interactions at the expense of genuine human connection [81]. Hence, safeguards must be implemented, including clear guidelines for ethical use, regular psychological assessments, and mechanisms to ensure that deepfake interactions support rather than replace authentic relationships [2].

At the same time, given the applied nature of the system, responsible AI [23] design must be considered. Modern conversational agents retain "memory" of previous interactions and personalise behaviour using techniques such as retrieval-augmented generation [49]. This typically involves accessing past conversation logs and user-specific information, which may be sensitive. It is, therefore, essential to protect such data through privacy-preserving methods and to incorporate robustness measures against adversarial attacks that could expose confidential content. Additionally, as re-enactment techniques [19] are used to enable emotionally engaging interactions, care must be taken to ensure that the synthesised behaviours remain faithful to the original reference material. In such cases, explainable or interpretable AI [1] can be used to trace which data contributed to a particular dialogue or generated output. Finally, as the aim is to create deepfakes that faithfully represent a wide spectrum of behaviours and appearances, it is important to incorporate bias-aware AI design.

To further mitigate psychological and ethical risks, a layered approach combining **pre-mission training, contextual framing**, and **adaptive system design** is recommended. Astronauts should be prepared in advance to understand the emotional limits and affordances of interacting with synthetic agents, reducing the risk of over-attachment [48]. Deepfake interactions could include subtle sensory cues to reinforce their artificial nature, enabling users to assess authenticity without disrupting emotional engagement [42]. Continuous psychological monitoring can inform dynamic adjustments to interaction frequency and tone, supporting individual mental health needs [5]. Moreover, governance should involve interdisciplinary oversight – ethicists, psychologists, and user representatives – to ensure responsible use and protect those whose likenesses are involved [27]. This ensures that deepfakes are used to augment, not replace, authentic relationships in space.

Furthermore, we identify two key research challenges. First, while most deepfake research to date has focused on mimicking visual and auditory signals [17], one significant sensory modality remains largely overlooked: **olfaction** [54]. Although smell cues may be subtle, they can play a crucial role in evoking a sense of social presence, for example, through

familiar scents such as perfume, aftershave, or shampoo. These smells often trigger emotional reminiscence and a sense of connection to loved ones. We argue that incorporating olfactory signals into deepfake experiences could further enhance emotional engagement [10]. Second, everyday life on Earth includes a range of emotionally charged experiences, both positive and negative. To help astronauts feel more "at home" during long missions, deepfake-enabled interactions should reflect this **emotional diversity**. Relying solely on overly comforting or idealized content could distort astronauts' perception and memory of social relationships, potentially making it more difficult to readjust to real-world interactions upon returning to Earth. The challenge lies in finding the right balance between positive and less positive interaction episodes to maintain emotional authenticity.

3.2 User Case 2: Task Planning and Backtracking in a Deep Space Scenario

Novel AI systems could be used in human spaceflight in fault management, recovery, and replanning during the execution of mission tasks. Automated planning of mission operations is not new, with various systems being already heavily used in spaceflight, such as NASA's ASPEN [31] and CLASP [63] task scheduling and planning systems. Such systems have extended capabilities of fault prediction and replanning. However, in some cases, the MCC still needs to be contacted in case a failure is external, task-related, and has elevated risk for the rest of the mission operations.

A prominent example is the recent micrometeoroid damage of the Space Station Remote Manipulator System (SSRMS, also known as Canadarm2). On May 12th 2021, astronauts onboard the ISS reported damage on the protective covering of the manipulator, caused by micrometeoroid impact. The damage was reported during a routine inspection, and high-resolution images of the damage were taken and sent to the MCC to assess the damage. The assessment of the images and the resulting state of the arm took more than two weeks, before the MCC concluded that the arm's performance was not affected, and that near-term operations could resume. Should such a failure take place on a lunar mission or mission to Mars, the communication latency in transmitting the fault images, combined with the time to perform fault analysis by the MCC could result in significant mission delays with potentially serious consequences.

This effect could be mitigated if the fault images were uploaded to an onboard server, where an AI agent could perform risk assessment. More specifically, Visual Language Models could be a fitting solution. Visual Language Models are generative AI models that can reason under both visual and text-based modalities [85]. They combine vision encoding with Large Language Models (LLMs) and can generate text responses from the combination of a given image and a text prompt. Their significance lies in their capability to handle both known problems in computer vision, such as out-of-class classification, and providing generative responses to tackle problems such as image summarisation and description. They have very recently started to be used as anomaly detection systems [41] and are being introduced to some more risk-averse industries and hazardous workspaces [14].

As fault detection systems, VLMs would be fed with a diagnostics image, such as a set of plots showing the change of a critical variable over time, and a text prompt. VLM would then reason over the fault detected after analysing the provided image and the text prompt, giving a generative response over the fault type and management. If such a system was used in the case of the ISS arm example, the astronauts could feed the images showing the arm damage to a VLM, along with graph data from diagnostics plots, and a text prompt asking whether the arm is operational. The result of the VLM could influence their decision to

continue with the scheduled operations without the need to contact the MCC, saving 14 days of operation time. Such systems would be valuable in cases of limited or very delayed communications, such as on future Mars missions.

Finally, task replanning after fault detection is another spaceflight operation that could benefit from AI and VLMs. Mission operation planners already incorporate some replanning capabilities based on potential fault cases, mostly related to system failures and faults. VLMs could instead be incorporated into the existing mission planners, to provide capabilities based on task failures. Such a paradigm has recently been demonstrated in robotic manipulation, where a robot extracts an image of a failed task, such as an unsuccessful grasp, identifies the task-specific failure mode, and replans an action to resolve it [76].

It should be noted that VLMs, similar to most learning-based algorithms, have significant implementation and reliability challenges that would need to be resolved before they are applied in the critical environment of space. One core limitation would be the lack of data: VLMs require vast amounts of data to be trained. In the context of spaceflight, the data required for training a VLM as a fault detection tool, such as user manuals and fault diagrams, may be too few for meaningful training or not accessible due to regulatory and commercial constraints. Model "hallucinations", meaning structurally consistent but not meaningful answers, should also be addressed in VLMs. These concerns were addressed in the context of LLMs in space operations, by the authors in [73]. To deal with the lack of data, the authors used a vector embedding of space systems documents combined with user queries on pre-trained LLMs, to evaluate their performance in answering queries related to system handbook search. To evaluate the hallucination performance, the authors inserted known information (system wiki pages, software documentation ea) into the vector embedding, and compared the answers to the inserted. The authors showed that LLMs returned useful answers while searching system handbooks, but with unpredictable and high hallucination rates, that depend on the prompt provided by the user. The authors stated that LLMs could be used as co-pilots in space operations, but the results depend on prompt engineering, potentially requiring hyperparameter tuning or re-training.

4 Conclusion

This paper offers a position on the integration of AI solutions to tackle challenges in space communications delay for human spaceflight. Our analysis focused on the need for resilient communication delays in human spaceflight, and we categorised these needs as task-based and social-based, i.e. as needs related to the mission objectives and operations, and needs related to the social communication between space crew and Earth. We provided a set of promising recent technologies that address these delays, from the fields of Human-in-the-loop AI, Digital twins, and Edge AI literature. We also described how cutting-edge technologies of deepfakes and VLMs could be integrated with existing spaceflight systems to mitigate the challenges posed by communication delays in deep space mission scenarios. Our paper provides a starting point for discussions in the introduction of novel AI techniques in human spaceflight for delay mitigation, as well as insights on the technologies that are most promising in this direction.

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Lighting Scenarios and Human Well-Being in Extreme Environments: Insights from St. Kliment Ohridski Antarctic Base

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Abstract

Lighting is a critical factor in human well-being, cognitive function, and performance – particularly in extreme and confined environments such as space habitats and Antarctic research stations. Despite its importance, limited research exists on how individuals adapt lighting to meet personal and contextual needs in these settings. This study investigates lighting use at the Bulgarian Antarctic base, focusing on how inhabitants adjusted natural and artificial light to support mood, comfort, and daily routines. Data was collected through on-site observations, qualitative interviews, and structured questionnaires. Results reveal key challenges in current lighting systems, including a lack of flexibility, user control, and emotional responsiveness. Findings suggest that human-centered lighting – especially systems that are adaptable, automated, and user-driven – can significantly improve well-being and operational efficiency in isolated environments. These insights inform future design strategies for space analogues and extraterrestrial habitats, contributing to the advancement of human-computer interaction in space exploration through responsive and personalized lighting solutions.

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contributed to the implementation and documentation of the project. Finally, we extend our sincere thanks to Georgios Tsakyridis for his valuable contribution in text editing and formatting, which supported the clarity and presentation of this work.

1 Introduction

As humanity advances toward deep space exploration and the development of space habitats, long-duration missions present growing challenges to the psycho-physiological well-being of astronauts. Confinement and isolation under unfamiliar environments and harsh conditions can affect humans both physically and mentally. Stress, anxiety, discomfort, sleep disruptions, headaches, disorientation, and even depression are only some of the common side effects on people who live and work for a period of time under extreme conditions [1].

Lighting design in those extreme, confined environments – such as space habitats and Antarctic research stations – plays a critical role in human well-being, performance, and psychological resilience [19]. However, research on user-centered lighting solutions in these settings remains limited, particularly in addressing long-term challenges like monotony, circadian misalignment, and adaptability to individual needs. Observations from both space analogues and polar bases reveal recurring issues: static lighting systems that fail to support dynamic human requirements, poor simulation of natural light cycles, and insufficient personalization.

Existing advancements in lighting for confined environments emphasize circadian rhythm regulation and basic task illumination, exemplified by innovations like SAGA Architects' Circadian Light Panel deployed on the International Space Station (ISS). This system uses tunable LEDs to mimic natural light cycles, promoting alertness or sleepiness in alignment with astronauts' biological clocks [6]. Prior studies in space analogues (e.g., HI-SEAS, Concordia Station) and polar bases have tested static LED solutions, but few incorporate real-time user feedback or AI-driven personalization. Similarly, analog habitats like LunAres have demonstrated the efficacy of artificial daylight simulation, where dynamic lighting cycles convincingly replicate natural rhythms. Participants in the Orpheus-11 mission reported no longing for natural sunlight, underscoring the psychological sufficiency of well-designed artificial cycles [11]. Despite these findings, most systems remain static, lacking adaptability to individual chronotypes or task-specific needs [8].

A growing body of research highlights the psychological benefits of color. Studies demonstrate that multicolor lighting is not only conducive to improving psychological comfort, work performance, safety, and environmental satisfaction but also helps reduce environmental stress and work fatigue as well as physical and mental problems [9, 23, 4]. Recent studies found that multicolour lighting can alleviate the increase in anxiety and negative emotions caused by isolation and confinement. Moreover, random changes of light color in the isolated environment appeared to help the participants increase their sense of surprise, thereby counteracting monotony [9].

Current lighting designs are configured to serve only one function, i.e., to support astronaut vision, not psychological issues. Therefore, exploring ways to alleviate psychological problems in a closed and isolated environment is an important means to ensure long-term space exploration and habitat missions [9].

Building on our previous research at TUC TIE Lab on artificial lighting and projection mapping for psychological comfort in modular space analogue habitats [1] – conducted as part of the Intelligent Spacecraft Module research framework – this study extends those insights to a new context: the Bulgarian Antarctic Base.

Our investigation was motivated by the need for automated, adaptive lighting systems that integrate Human-Computer Interaction (HCI) principles for long-duration missions, extending concepts explored under the Sensponsive framework and the Spirit-Ghost pilot projects. The presented research explores further the work done for a Mars habitat prototype, emphasizing reconfigurable environments [21] and the Intelligent Spacecraft Module, a self-adapting habitat leveraging AI for crew comfort [20].

We hypothesized that AI-driven, user-customizable lighting – informed by these prior initiatives – could mitigate isolation, enhance task performance, and regulate circadian rhythms, addressing both observed deficiencies in Antarctic lighting systems and astronaut needs in space exploration.

The findings highlight key challenges in current lighting setups and underscore the need for adaptive, AI-driven, human-centered systems that adjust in real time to users' needs [18] and prioritize astronaut well-being in confined, isolated habitats like Mars bases or lunar stations. This study advances human-computer interaction (HCI) research in space exploration and aims to bridge the gap between technical lighting systems and human experience by informing the development of intelligent lighting systems tailored for long-duration missions in space analogues and extraterrestrial habitats.

2 Methodology and Field Deployment

To explore these issues in a real-world analogue environment, the present study employed a three-phase experiment procedure at the St. Kliment Ohridski Base, combining quantitative and qualitative approaches to investigate the psychological and experiential impact of adaptive, multicolour lighting in confined and isolated conditions. The research was conducted by the co-author at the Bulgarian Antarctic base between 28th December 2024 and 18th January 2025. Phase A was conducted during the initial weeks of the expedition, followed by Phase B over a 20-day intervention period and Phase C after the departure of the co-author of the base.

Phase A: Baseline Assessment of Lighting Perception in Confined Environments

The initial phase involved the administration of the Lighting Questionnaire for Confined Environments, developed to evaluate subjective perceptions, preferences, and psychological responses to lighting among individuals living and working at the St. Kliment Ohridski Base. The questionnaire consisted of both quantitative and qualitative components, enabling the collection of measurable data alongside open-ended reflections on lighting conditions in confined spaces. A total of 20 participants, residing across all buildings of the base, participated in this phase.

Phase B: Qualitative Findings from the Experiential Phase – Researcher and Inhabitant Views

In the second phase, a colorful lighting fixture was installed by the researcher in the Casa España for a period of approximately 20 days. A total of four participants, all residents of Casa España, participated in this second, experiential phase. The aim was to explore the emotional, cognitive, and experiential dimensions of lighting in a lived setting. To evaluate the intervention's impact, the Casa España Questionnaire was administered to the inhabitants. This eight-question instrument focused on participants' initial impressions, emotional and psychological responses, memory associations, and openness to the future use of colorful lighting in extreme environments.

Phase C: Post-Intervention Interaction with Adaptive Lighting

Following the researcher's departure from the base, the lighting fixture remained in place for continued, voluntary use by all of the inhabitants of the base. Observational material and informal feedback were subsequently collected to document spontaneous interactions with the lighting and to gain insight into longer-term engagement with the installation.

Overview of Lighting Devices for the Study

Two lighting fixtures were employed in the experiment to explore the psychological and atmospheric effects of dynamic lighting in confined environments. The first was an RGB Sunset LED lamp (Figure 1), featuring integrated LED technology and remote control.



Figure 1 Lighting Fixtures used in the experiment: RGB Sunset Led lamp.

It provides a full RGB spectrum, allowing users to adjust color, intensity, and transitions to create mood-specific lighting. Its gradient sunset effect was used to enhance emotional comfort, supporting both relaxation and social interaction through customizable ambient colorful light [3].

The second fixture was a high-output RGB stage-effect lamp (Figure 2), equipped with three 1W LEDs in a compact, portable form. With a 120° beam tilt and both auto and remote modes, it enabled vivid, moving, spatially adaptable lighting scenarios [26]. Its dynamic projections were suited for both decorative and atmospheric purposes, enhancing spatial perception and variability in the experimental interiors.



Figure 2 Lighting Fixtures used in the experiment: LED "disco" lamp.

Together, these phases aimed to assess whether adaptive, multicolor lighting could meaningfully impact psychological well-being, spatial perception, and social dynamics – providing insight for future human-centered lighting strategies in long-duration space missions.

3 Sensponsive Lighting in Extreme Environments: From Philosophical Foundations to Adaptive Applications

a. The Philosophy of Sensponsive Design: Time, Understanding, and Intention in Adaptive Environments

Sensponsive design framework is an architectural and technological approach that integrates real-time sensing, artificial cognition, sensibility and response through adaptive spatial and ambience configurations to create environments that respond dynamically to human activity, specifically tailored according to the context of the activity. The term derives from the notion of "sensible responses" meaning that the provision of any response should take into consideration a multitude of factors that give "meaning" to the human actions and provide beneficial conditions to facilitate the performance of these actions in the appropriate context. The framework also emphasizes seamless and "transparent" interaction between users and spaces via embedded systems and smart materials. Rooted in ambient intelligence and ubiquitous computing, sensponsive design adjusts spatial and ambient conditions based on behavioral and contextual data. It is guided by three core principles: time (prompt responsiveness), understanding (contextual and behavioral awareness), and intention (purposeful, user-centered adaptation) – together enabling intelligent, comfort-driven environments [17, 18, 19]. The advancement of AI provided the tools to pursue further research and development of the Sensponsive framework, allowing proof-of-concept projects to move forward.

b. The Evolution of Lighting in Extreme Environments: From Functional Illumination to Sensponsive Intelligence

The evolution of lighting in confined and isolated environments has progressed in response to a deepening understanding of human needs in extreme conditions. Early stages relied on simple, functional solutions such as static fluorescent lighting, primarily aimed at providing visibility and supporting basic operational tasks.

Currently, lighting systems have advanced to simulate circadian rhythms, recognizing the critical role of light in regulating biological cycles, sleep patterns, and general well-being in environments where natural light is absent or inconsistent [6, 5, 12]. Alongside this, there is a growing focus on using light to foster relaxation, recreation, and social interaction, incorporating dynamic color temperatures, ambient lighting tones, and mood-enhancing schemes to improve the overall quality of life in such settings [9, 5].

Looking ahead, the next frontier in lighting design is the development of personalized and intelligent lighting systems powered by artificial intelligence (AI), the sensponsive lighting systems, as well as systems that provide the illusion of deeper fields of view, mitigating the issues resulting from confined lines of sight and restricted fields of view. These systems aim to be both activity-based and context-sensitive, adapting in real time not only to the nature of the activity being performed but also to the individual characteristics and preferences of each user [17, 18, 19].

The goal is to create a lighting environment that understands and responds to both functional demands [25] and emotional states, offering differentiated lighting experiences even among users engaged in the same task. That marks a transition toward truly adaptive, human-centered lighting ecosystems, where AI enables deeper personalization and enhances well-being through responsive environmental design.

c. Towards Sensponsive Lighting: Applying Adaptive Design Principles in Extreme Confined Spaces

In extreme environments like space stations and Antarctic bases, lighting plays a critical role in mitigating the effects of isolation, light deprivation, and psychological strain [5]. Traditional static systems often overlook evolving human needs and environmental shifts [19]. Sensponsive lighting addresses that by using predictive cognitive-based intelligence and real-time situation awareness to adapt light conditions based on both contextual activity and individual user preferences [17]. These systems analyze user behavior, movement patterns, and the time of day to anticipate needs [18] – whether for work, rest, or focus – and adjust brightness, color temperature, and intensity accordingly. Over time, they learn from user interactions to fine-tune lighting to personal comfort levels. This personalized, context-aware approach enhances well-being, resilience, and performance in confined, high-stress settings.

4 Illumination in Isolation: Shared Constraints and Divergent Needs in Antarctic and Space Habitats

Antarctica and space habitats share similar lighting challenges due to isolation and environmental extremes. While Antarctica has a natural day-night cycle, it is highly irregular – with months of continuous light or darkness – offering limited support for circadian regulation [12]. In contrast, space habitats lack natural light entirely. Both settings typically rely on pre-programmed, centrally managed lighting systems that limit user control and provide uniform, task-focused illumination – lacking the flexibility needed to support psychological comfort or accommodate varied activities [8]. That can disrupt sleep patterns and the feeling of adaptation [15, 16] and reduce overall well-being [5]. To address these constraints, lighting design must move beyond basic functionality to support circadian rhythms, emotional well-being, and adaptability in these extreme contexts.

5 Research Context and Environmental Conditions

a. Site Description and Spatial Configuration

St. Kliment Ohridski Base is a Bulgarian Antarctic research station located on Livingston Island in the South Shetland Islands, off the coast of the Antarctic Peninsula. The station is situated on slightly elevated, ice-free terrain near the coast of South Bay, adjacent to the Grand Lagoon – a freshwater body covering approximately 10,000 square meters and situated at an elevation of 2.4 meters above sea level.

Unlike single-structure research stations such as Concordia, St. Kliment Ohridski Base comprises a network of buildings, each serving distinct functions. Constructed at different periods, these structures collectively form the base's infrastructure, facilitating transitional spaces and movement pathways between them. Currently, the base consists of 11 separate building premises, each fulfilling specific operational, residential, or research-related roles (Figure 3).

b. Lighting Conditions and Environmental Context

b1. Daylight Conditions During the Research Period

The lighting conditions observed during the experiment, conducted between December 28th, 2024 and January 18th, 2025, coincided with the peak of the Antarctic summer [22]. During this period, the base experienced continuous daylight, with only slight variations in ambient

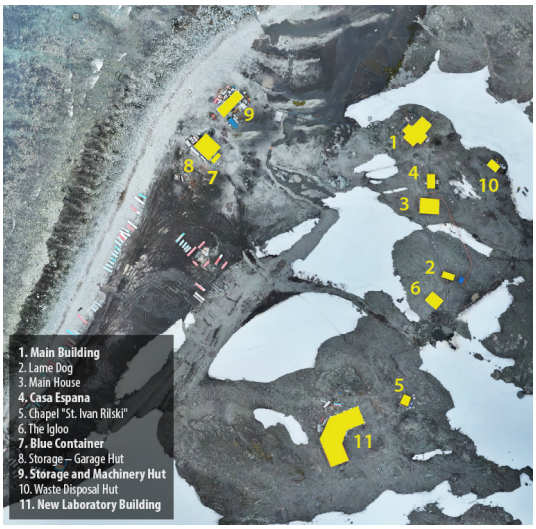


Figure 3 Masterplan of St. Kliment Ohridski Base.

light intensity throughout the 24-hour cycle. The darkest interval occurred between 01:00 and 03:00 AM, although the sky retained some brightness. From 08:00 AM to 09:00 PM, changes in daylight were minimal and barely perceptible (Figure 4). Despite the extended photoperiod, the most significant variations in lighting were due to weather conditions rather than diurnal shifts (Figure 5).



Figure 4 Typical Daylight Progression at St. Kliment Ohridski Base (photo credit: Balomenaki C., Gouroundi E.).



Figure 5 Contrasting Daylight Conditions at St. Kliment Ohridski Base (photo credit: Balomenaki C., Gouroundi E.).

The variability in lighting conditions at the base was primarily driven by the rapid and unpredictable meteorological changes. The weather in the region was highly dynamic, often shifting rapidly over short periods. The overcast sky and the landscape in grayscale tones

were often obscuring the characteristic hues of sunset and its colors. On some occasions when the clouds parted, the contrast was dramatic: clear blue skies delivered high-contrast illumination, enriching visibility and enhancing color perception across the terrain. These brief moments of improved visibility prompted excursions – such as hikes to nearby peaks – to observe and document the vivid hues of the Antarctic sunset. That resulted in a diverse and often challenging lighting environment for both observational and experimental activities.

Here is a personal testimony from architect Penka Stantcheva – who spent a year overseeing the construction of new laboratories at the Bulgarian Antarctic Base "St. Kliment Ohridski" – and conveys the lighting experience exceptionally well: *"The light – it's different every day, changes several times a day. At that moment of the year day and night merge; practically, it doesn't get dark. Over time one starts getting used to it, recognizing the subtle shades of light that suggest the time. Dynamic climate changes, the onset of rain, as well as the often shifts of clouds, winds and lights also contribute to the feeling that one day consists of many days"* [24].

b2. Interior Lighting Conditions: Daylight and Artificial Lighting

Dining Hall in the Main Building

At the heart of the base lies the Main Building (Figure 6a), a single-story structure functioning as the central hub of daily life. It includes shared living spaces, such as a dining area, an open-plan kitchen, and common rooms where residents engage in leisure activities. Bedrooms and bathrooms are also located within the structure, and a food storage area is found at its rear.



Figure 6 (a) Main Building (photo credit: Balomenaki C., Gouroundi E.), (b) Casa España (photo credit: Balomenaki C., Gouroundi E.), (c) Blue Container (photo credit: Velikova M.), (d) New Laboratory Building (photo credit: Balomenaki C., Gouroundi E.).

The Dining Hall in the Main Building stands out as the space with the most generous daylight access across the entire base. It features three large windows, each measuring 60 × 90 cm, oriented toward the southeast, southwest, and northwest. This strategic orientation provides consistent exposure to daylight throughout the day while also offering visual contact with the surrounding Antarctic landscape. Particularly, the southwest-facing window, which opens toward the bay, is a favorite spot among base residents for its unobstructed view and the vivid colors of the sunset when visible.

The Dining Hall is characterized by warm wooden surfaces, on which the artificial lighting projects prominently. In terms of artificial lighting, it offers the most thoughtfully designed and atmospherically rich setup within the base. It is the only space where, even at a basic

level, lighting scenarios had been implemented during the researcher's stay. A combination of pendant lights and decorative string lights creates a warm, domestic ambiance. The capacity to vary the lighting configuration contributes significantly to the perceived intimacy and emotional comfort of the space, distinguishing it as a key area for social gathering [3, 15] (Figures 7, 8).

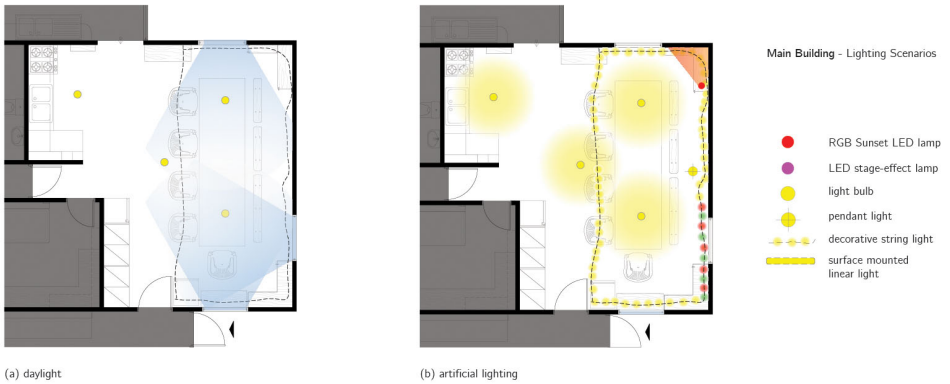


Figure 7 Lighting Scenarios in the Main Building: (a) Daylight, (b) Artificial lighting.



Figure 8 (a) Christmas string lights in the dining room, originally temporary but kept for their atmospheric effect until 18th of January (photo credit: Gouroundi E.), (b) Daylight conditions of the dining room (photo credit: Nedkov K.).

Casa España

Adjacent to the main facility is Casa España (Figure 6b), a two-story building with sleeping accommodations for up to three people on the upper floor and two people on the ground floor. The ground floor features a small workspace and bathroom. Its interior, entirely clad in natural-colored wood, responds dynamically to lighting conditions. As with the dining hall, the interaction between artificial light and the wooden surfaces creates a visually rich and textured environment, again marked by high visual complexity.

The ground floor of Casa España presents limited access to daylight. The space includes only one small, high-level window that prevents any meaningful visual connection with the exterior. As a result, natural light is insufficient, and artificial lighting becomes necessary

for most of the day. The artificial lighting in Casa España consists of a single type: surface-mounted linear lights with a cool color temperature. The setup provides uniform, functional illumination but lacks flexibility or variation. No lighting scenarios are implemented in this space, which remains visually static and functionally utilitarian throughout the day (Figures 9, 10).



Figure 9 Lighting Scenarios in Casa España: (a) Daylight, (b) Artificial Lighting, (c) Colorful Lighting.



Figure 10 (a) Daylight conditions in the common area of Casa España, (b) use of the RGB Sunset LED lamp in the common area during the ambient lighting experiment (photo credit: Balomenaki C., Gouroundi E.).

The "Blue Container"

The Blue Container (Figure 6c), a repurposed standard-sized shipping container (6.06 m × 2.44 m), serves a versatile role, commonly used as a laboratory for scientific research. Its interior, finished in a light grey palette, offers minimal visual complexity. This uniformity, combined with its small scale, results in optimal conditions for controlled lighting, making it ideal for work that requires visual clarity and consistency.

The Blue Container benefits from excellent daylight conditions due to the presence of three large windows on three sides of the space. It is the only building on the base equipped with shutters, allowing full control over the amount of daylight entering the interior. This makes it particularly suitable for activities that require variable or reduced light levels, including scientific observations. Artificial lighting in the Blue Container is purely functional, composed of two surface-mounted linear lights emitting cool white light. The emphasis here is on visual clarity and task performance, aligning with the container's role as a multi-purpose research and work area (Figures 11, 12).

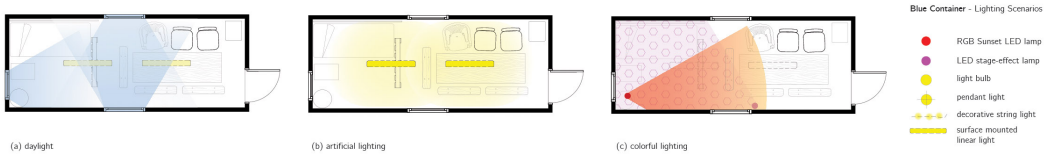


Figure 11 Lighting Scenarios in the Blue Container: (a) Daylight, (b) Artificial Lighting, (c) Colorful Lighting.



Figure 12 (a) Daylight Conditions in the "Blue Container", (photo credit: Balomenaki C., Gouroundi E.), (b) interior view showing its use as a social area with both lamps in operation (photo credit: Stefanov R.).

Storage and Machinery Hut

The Storage and Machinery Hut features an open-plan storage room at its front, characterized by a sparse layout and minimal furnishings. This simplicity results in low visual complexity, making it easier to observe and analyze the effects of lighting within the space.

The open-plan storage room benefits from substantial daylight input via three northwest-facing windows and two southeast-facing ones. These provide balanced natural lighting conditions throughout the day, especially during periods of clear weather. Artificial lighting is provided by ceiling-mounted linear lights, ensuring even and practical illumination across the large, open space. Uniquely, this room also features five fixed-color LED bulbs installed along the northeast wall. Along with the Dining Hall, it is one of only two spaces in the base with provisions for colored lighting, enabling alternative atmospheric scenarios. This feature adds an unexpected layer of flexibility in an otherwise functional environment (Figures 13, 14).

The New Laboratory Building

The most recent addition to the base infrastructure is the New Laboratory Building (Figure 6d), completed during the latest research season. While it is scheduled to become fully operational in the following season, its common areas were already accessible. These spaces are defined by a modern interior design with light grey walls and ceilings and a laminated floor.

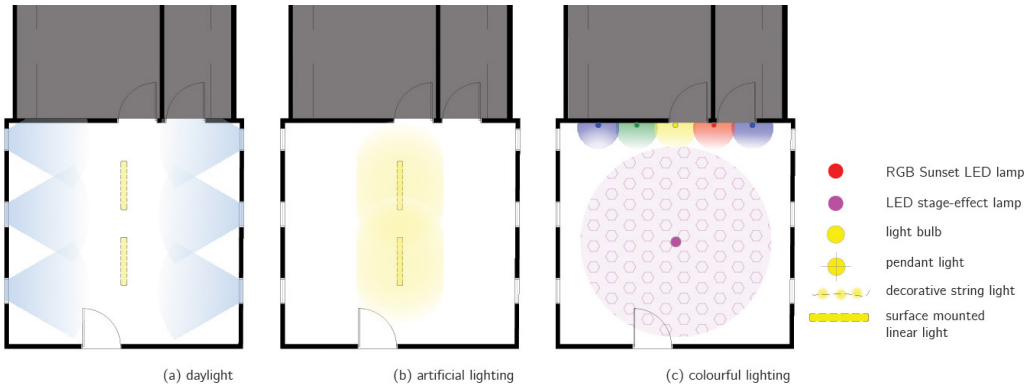


Figure 13 Lighting Scenarios in the Storage and Machinery Hut: (a)Daylight, (b) Artificial Lighting, (c) Colorful Lighting.



Figure 14 Use of the portable RGB "disco" lamp during socializing events (photo credit: Nedkov K.).

The Common Space is notable for its extensive access to daylight. It includes five windows, three of which are large horizontal openings that frame panoramic views of the bay. The combination of light grey interior surfaces with the wooden flooring enhances the quality and diffusion of natural light, creating a pleasant and calming atmosphere that supports both relaxation and collaborative activities. Artificial lighting is embedded in the ceiling through a recessed system integrated into a suspended ceiling structure. This type of lighting provides uniform, ambient illumination while maintaining the minimalist aesthetic of the space (Figure 15).

6 Lighting Questionnaire for Confined Environments – analysis

The questionnaire aimed to gather qualitative and quantitative feedback to (1) assess the impact of lighting conditions (e.g., color temperature, intensity, and customization) on well-being, task performance, and mood in confined environments; (2) evaluate satisfaction with existing lighting systems (e.g., circadian rhythm alignment, comfort); (3) identify current challenges (e.g., monotony, poor task support, isolation); and (4) guide user-specific lighting strategies for long-duration missions in space analogue environments.

The study involved 20 participants (13 males, 7 females) occupying diverse professional roles at the Antarctic base, including engineers, scientists, medical staff, architects, and logistics personnel. Ages ranged from 26 to over 56, with most participants between 36



Figure 15 Evening Lighting Conditions in the New Laboratory building (photo credit: Nedkov K.).

and 56. Several held dual roles, combining research with technical or administrative duties. Antarctic experience varied significantly – from first-time deployments to veterans with up to eight missions. Most had visited once (9 individuals), while others had between two and eight seasons of experience. This diversity provided a broad range of perspectives, enriching the study's insights into how occupational and environmental factors impact well-being and habitability in extreme conditions (Table 1).

Participants provided demographic details, including age group, profession, and prior experience in confined environments. The questionnaire was categorized into five thematic groups for analysis:

- Demographic Characteristics
- Lighting Preferences & Customization
- Evaluation of Current Lighting Conditions
- Engagement with Colorful Lighting and Mood Effects
- Suggestions & Improvements

6.1 Demographic Characteristics

The demographics of the participants (i.e., age, gender, occupational role or position at the base, duration of stay, and prior experience in confined environments) played a significant role in the results of the research.

Age. Younger participants (26–35) valued customization and embraced flexibility, while older ones (46–55+) prioritized functional aspects like task efficiency and visual comfort. The results indicated that age can influence circadian sensitivity, tolerance to artificial lighting, and openness to technology (like AI-based lighting).

Occupation & Role. People with technical or leadership roles (e.g., engineers, scientists, base commanders) focused on functional, task-oriented lighting and did not engage much with colorful lighting, as they seemed to prioritize basic needs and value control and stability over change. People with more diverse backgrounds (e.g., architects and artists) were more sensitive to monotony and needed dynamic lighting to maintain mental well-being. These individuals found colorful lighting engaging and mood-boosting.

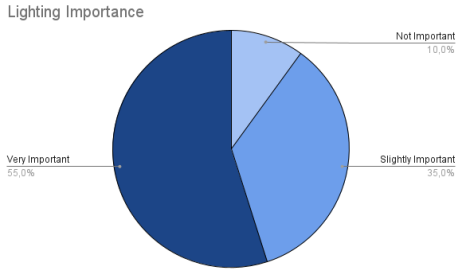
Table 1 Demographic Data of Participants in the Lighting Questionnaire for Confined Environments.

ID	Gender	times in Antarctica	Occupation	Age Range	Role / Description
1	Male	4	Electrical Engineer	46–55	Electrical Engineer
2	Male	7	Engineer	36–45	Research Engineer
3	Male	2	Electrical Engineer	36–45	Electrical equipment support, scientist assistance
4	Female	4	Boat Driver	36–45	Logistics and safety
5	Male	2	Mechanic	26–35	Logistics work
6	Male	1	Electrical Engineer	46–55	Manager of electrical company
7	Male	1	Electrical Engineer	46–55	Electrical work in new building construction
8	Female	2	Musician	46–55	Researcher
9	Male	6	—	36–45	Base commander, general support
10	Male	7	Doctor	46–55	Base doctor
11	Male	1	Engineer	36–45	Logistics work
12	Male	1	Prof. Assistant	26–35	Science experiment
13	Male	1	CEO	36–45	Scientist / Observer
14	Male	1	Scientist	46–55	Scientist
15	Male	8	Scientist	56+	Manager
16	Female	1	Scientist	36–45	Administrative
17	Female	1	Civil Engineer	36–46	Civil Engineer
18	Female	2	Medical Doctor	26–35	Medical Doctor
19	Female	1	Architect	26–36	Scientific Experiment
20	Female	1	Architect	26–37	Researcher

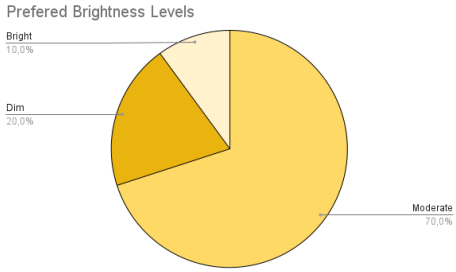
Hours Indoors (Range: <6 to 14+ hours daily). Participants who worked more than 10 hours per day indoors reported higher sensitivity to unnatural light cycles and valued customization and brightness and demanded activity-based dynamic adjustments. Those working outside were less critical of static lighting and preferred indirect or natural lighting.

6.2 Lighting Preferences & Customization

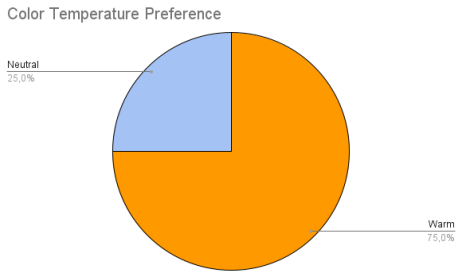
Participants generally valued the role of lighting in their daily routines (Figure 16a). Most expressed a strong preference for warm, dim lighting with moderate brightness, likely due to its calming and comforting effects (Figures 16b and 16c). Customizable lighting solutions were highly appreciated, as many users expressed a clear desire to adjust settings according to personal preferences (Figure 16d). Greater control over brightness and color temperature enhanced comfort and well-being, reinforcing the importance of adaptable, user-centered lighting in confined environments [14].



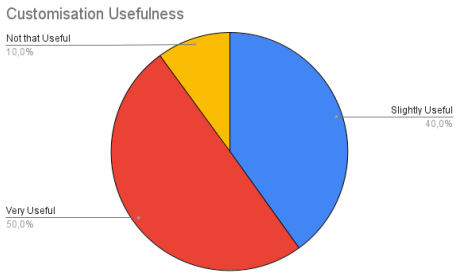
(a) Lighting Importance.



(b) Preferred Brightness Levels.



(c) Color Temperature Preference.



(d) Customisation Usefulness.

Figure 16 Participant Feedback on lighting preferences and perceptions: (a) Lighting Importance, (b) Preferred Brightness Levels, (c) Color Temperature Preference, (d) Customisation Usefulness.

6.3 Evaluation of Current Lighting Conditions

The current lighting conditions were generally functional but lacked adaptability and personalization. Repeated expeditions appeared to foster emotional investment, leading experienced participants to offer sharper critiques. People with multiple expeditions reported higher satisfaction but emphasized the need for AI-driven adaptability, while those with fewer than four missions showed more varied responses (Figure 17). This variability underscores the importance of personalized lighting solutions, where one-size-fits-all approaches fail to address individual preferences and requirements. Overall, the findings highlight the need for more dynamic, user-responsive lighting systems to enhance both performance and well-being in isolated environments.

6.4 Engagement with Colorful Lighting and Mood Effects

Engagement with colorful lighting received mixed responses (Figure 18a). While some participants found it helpful in breaking monotony, others did not find it engaging. People who valued colorful lighting tended to be more sensitive to isolation and relied on dynamic environments to support their well-being. In contrast, participants with technical or leadership roles, who prioritized functionality and stability, were less affected by environmental monotony and valued control over change.

Overall, colorful lighting proved most effective in social settings or unexpected situations, but its mood-boosting effects were inconsistent, highlighting the need for adaptable, user-specific lighting strategies (Figure 18b). Participants strongly valued the ability to personalize their lighting environment, with many explicitly requesting customizable features to suit their individual needs (Figure 18c). Notably, the ability to customize lighting played a key

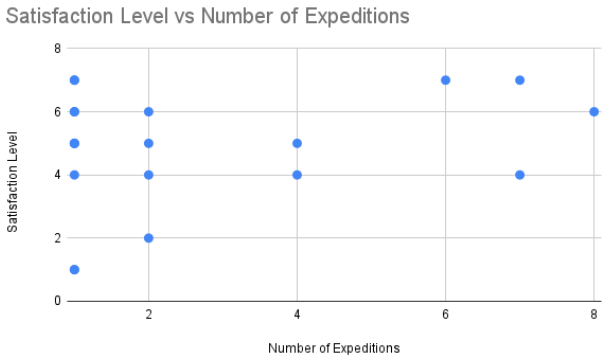
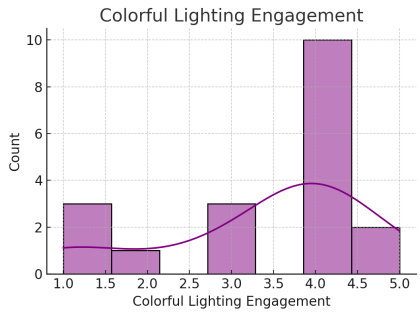
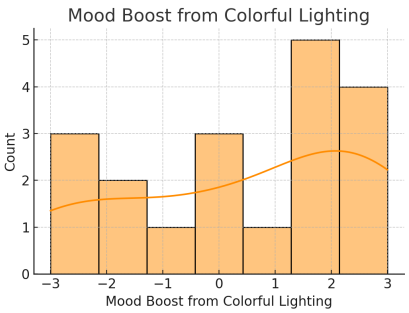


Figure 17 Satisfaction Level vs Number of expeditions.

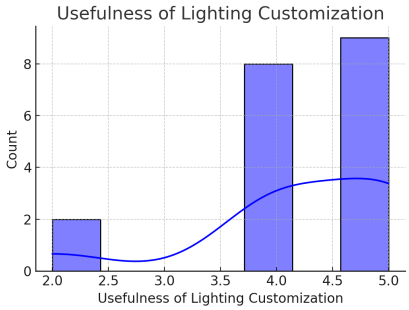
role in reducing feelings of isolation, particularly among participants who spent extended periods indoors, reinforcing the importance of adaptable, user-centered lighting in confined environments (Figure 18d).



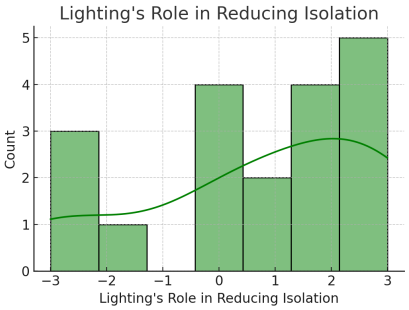
(a) Colorful Lighting Engagement.



(b) Mood Boost from Colorful Lighting.



(c) Usefulness of Lighting Customization.



(d) Lighting's Role in Reducing Isolation.

Figure 18 Participant Responses to the psychological and emotional effects of colorful and customizable lighting : (a) Colourful Lighting Engagement , (b) Mood Boost from Colorful Lighting, (c) Usefulness of lighting Customization, (d)Lightning's Role in Reducing Isolation.

7 Qualitative Findings from the Experiential Phase: Researcher and Inhabitant Views

a. Uses of Colourful Lighting Prior to the Intervention

Before the implementation of the experimental lighting setup, the use of colorful lighting at the St. Kliment Ohridski Antarctic Base was limited but intentional, primarily associated with social events and festive occasions. These lighting choices were not part of a formal design strategy but emerged organically as responses to the need for psychological relief and atmospheric variation in an otherwise functionally lit environment.

One notable example was the use of a portable RGB "disco" lamp during special social events [3], first observed by the researcher on New Year's Eve (Figure 14). This lamp was set up in the storage room of the machinery and storage hut – an open, empty space that posed minimal risk of interfering with scientific equipment or disturbing those resting in nearby quarters. Its temporary installation in this isolated location highlights the importance of minimizing disruptions while still providing opportunities for social engagement and mood enhancement through dynamic lighting.

Interestingly, the storage room is also the only space within the base that includes permanently installed colorful lighting. Five LED lamps are fixed along the walls – two blue, one red, one white, and one green – creating a vivid and playful lighting environment. Though the space serves a utilitarian function, its lighting makes it the most visually dynamic and playful area of the base, offering a stark contrast to the otherwise neutral and task-oriented lighting found throughout the station. This ambient shift further reinforces the room's role as a preferred location for social events and recreational gatherings.

Another instance of colorful lighting was the use of string lights in the dining room (Figure 8a). Although initially installed as a seasonal decoration before the Christmas period, these lights remained in place well after the holidays due to their calming and atmospheric qualities. The string lights were eventually taken down on 18th January 2025. As the dining area is a central social space within the base, the continued presence of the soft, colorful lighting contributed to a more relaxed and inviting environment during communal meals and informal gatherings. Figure 7 provides a view of the dining room during evening hours, with the Christmas lights softly illuminating the space, adding warmth and informality to one of the base's most frequently used communal areas.

These informal and user-driven lighting decisions reflect an intuitive understanding of the psychological impact of lighting in extreme and confined environments [5]. They also suggest a hypothesis: even in the absence of formal design interventions, base personnel instinctively gravitate toward lighting choices that provide emotional comfort, visual variety, and a sense of normalcy – elements later explored more systematically through the experimental phase of this study.

b. Experiential Phase During the Researcher's Presence

b1. Use of the RGB Sunset LED Lamp in Casa España

The RGB Sunset LED lamp was introduced to Casa España by the researcher as part of the experimental exploration of ambient lighting in isolated and extreme environments. The house was inhabited by five individuals (the researcher included) – three residing on the upper floor and two on the ground floor. The lamp was installed by the researcher on the ground floor, positioned on the working table adjacent to the side wall (Figure 10b). This floor also served as the common area of the dwelling, used collectively by all inhabitants.

The strategic placement of the lamp in this shared space, as opposed to the more private upper floor, allowed for broader access and communal use, reinforcing the lamp's integration into the collective life of the house.

Although the lamp was primarily used by the researcher – especially at night before sleep – it was also used freely by the second ground floor inhabitant and occasionally by others residing on the upper floor. Despite the lamp's wide range of RGB settings, the researcher intentionally limited its use to the "sunset colours" mode, without modifying hue or brightness throughout the experiment. This consistent use of warm, sunset-toned lighting maintained a stable visual and emotional atmosphere in the shared space.

The ground floor's function as both a communal and transitional space made it a significant site for observing how ambient lighting could influence daily rhythms and shared perceptions in a confined, polar environment. The lamp, by virtue of its presence and strategic placement, became a subtle yet meaningful feature of the occupants' routine in Casa España.

b2. Researcher's Self-Reflection on Ambient Lighting

The initial intention behind the installation of the RGB Sunset LED lamp was to experiment with the effects of warm lighting as a countermeasure to the absence of night and the persistent exposure to white light – both from artificial sources and the prolonged Antarctic daylight [22]. However, the researcher observed that the impact of the lamp extended far beyond its initial experimental scope.

The constant daylight and sterile white lighting of the environment produced greater physical and cognitive fatigue than anticipated [12]. This continuous exposure made relaxation and sleep initiation increasingly difficult. In this context, the RGB Sunset LED lamp became a personal necessity. Not a single night passed without the researcher using the lamp, even briefly. On most evenings, it was also used during late working hours or for personal activities in Casa España, particularly in the late afternoon and nighttime periods. What began as a design-led intervention evolved into a daily coping mechanism [10]. The consistent, warm gradient of the light helped mark the transition from work to rest [2], simulating the sense of dusk in an environment devoid of natural nightfall.

This ritualistic use of the lamp was not only psychologically comforting but also seemed to reflect a broader experience shared by the other inhabitants. This hypothesis was subsequently tested through the Casa España Questionnaire, which the researcher distributed after removing the lamp from the house. The qualitative results of that survey, presented in the following section, offer further insight into the collective emotional and psychological responses to ambient lighting in extreme environments.

b3. Demographic Characteristics of Participants

The participant group comprised individuals with diverse professional backgrounds and varying degrees of Antarctic experience. The sample included primarily female participants, all of whom held roles as researchers in fields such as geology, seismology, architecture, and music. Ages ranged from 26 to 55 years, with the most common age bracket being 36–45. Experience in Antarctica varied notably, with time spent on the continent ranging from a single visit to as many as seven expeditions (Table 2). This diversity offers a multifaceted perspective on the perception of lighting conditions in St. Ohridski Base.

Table 2 Demographic Data of Casa España Questionnaire Participants.

Participant	First Impression	Emotional Impact	Future Use	Memory Association	3 Descriptive Words
1	Surprised, liked it	Positive, uplifting	Yes	None	Calm, warm, comforting
2	Strange, neutral	Neutral/unpleasant	No	Disco light	Dark red circle
3	Focused on warm tones	Uplifting, essential	Absolutely	Familiar home lighting	Calm, focusing, warm
4	Comfortable	Relaxing, at home	Definitely	Winter holiday streets	Winter holidays, comfort, relaxation

b4. Emotional and Psychological Responses: Casa España Questionnaire Analysis

The "Questions for the Inhabitants of Casa España" questionnaire was designed to explore the emotional, psychological, and experiential impact of colorful lighting administered at Casa España. The questionnaire aimed to assess how experimental lighting influences mood, well-being, and subjective perception in isolated and extreme environments. Consisting of eight open-ended and multiple-choice questions, the questionnaire focuses on first impressions, emotional resonance, and personal reflections elicited by the lighting installation.

Participants were asked to evaluate their initial reactions (Questions 1–2), the emotional and mental effects of the lighting (Questions 3–4), and their openness to adopting similar lighting solutions in future expeditions (Questions 5–6). The questionnaire also probes personal associations and memory recall (Question 7), and invites participants to summarize their experience using three descriptive words (Question 8). The responses of four inhabitants were analyzed thematically to extract common patterns and notable individual variations (Table 3).

Table 3 Thematic Summary of Responses from Casa España Questionnaire Participants.

ID	Gender	times in Antarctica	Occupation	Age Range	Role / Description
1	Female	1	Geologist	36–45	Researcher
2	Female	7	Seismologist	36–45	Researcher
3	Female	1	Architect	26–35	Researcher
4	Female	2	Musician	46–55	Researcher

First Impressions and Initial Reactions. Participants expressed a range of first impressions. Two respondents described the lighting as surprising and enjoyable, while one noted it as "strange," with a neutral to negative impression. One participant found the lighting immediately comforting. That suggests that colorful lighting produced an unexpected shift in environmental perception for most, though not all, inhabitants.

Participant 1 noted, *"It surprised me and I really liked it,"* highlighting the significance of surprise as a positive emotional trigger in monotonous environments. In settings where routine and sensory uniformity dominate – such as Antarctic bases or space habitats – this element of surprise can break the psychological inertia of monotony. Particularly in space environments, where external stimuli are minimal and the visual landscape remains unchanged, the capacity of dynamic lighting to introduce unexpected visual and emotional variation may serve as a low-tech yet powerful countermeasure to monotony-induced fatigue and psychological stagnation [5].

Notably, Participant 2 – who characterized the lighting as "strange" – had by far the most extensive experience in the base, having participated in seven expeditions and having previously resided in Casa España. In fact, she was the only participant who had previously inhabited this exact space, as Participant 4 (though also experienced) had stayed in different accommodations in the past mission. This background raises an intriguing question: does the "strangeness" she reported reflect a moment of a disorienting unfamiliarity within the familiar?

Emotional and Psychological Impact. Three out of four participants reported a distinctly uplifting, relaxing, or mentally beneficial experience. This aligns with controlled experiments showing that low-illuminance, warm dynamic light environments foster lower stress and greater emotional well-being [13]. Participant 3 emphasized its function as a psychological "anchor" and social signal, noting that *"if the lamp was on, someone was in Casa España, or someone cared enough to light it."* This echoes findings by Helliwell, as reported by Mikkel Bille and Tim Flohr Sørensen, who observed that the absence of light during her illness signaled distress to others, highlighting light's role as an index of social and emotional presence [3]. The fourth participant reported no psychological benefit, highlighting individual variability in lighting perception.

Participant 1 remarked, *"It was definitely nice to see warm colors after a whole day of monotonous landscapes,"* referring specifically to the surrounding glaciers near the base. While these icy terrains are widely regarded as places of exceptional natural beauty, their predominantly grayscale color palette can quickly become visually monotonous when encountered daily. Notably, this participant was experiencing Antarctica for the first time and had been at the base for only one month during the study – underscoring how quickly environmental novelty can give way to perceptual habituation. This response illustrates the psychological value of warm, dynamic lighting as a counterbalance to sensory uniformity. It suggests that even awe-inspiring landscapes, when experienced under conditions of isolation and routine, may contribute to monotony. This further reinforces the need for atmospheric lighting design that introduces visual warmth and variation as a countermeasure to the grayscale Antarctic landscape to support mental stimulation and emotional well-being in extreme and confined environments [9, 5].

Future Use and Recommendations. The majority of respondents indicated that they would use and recommend such lighting in future expeditions, recognizing its value in supporting mood and well-being. One participant was reluctant, reflecting differing preferences and the need for adaptable lighting strategies.

Memory and Personal Associations. Several participants connected the lighting with memories of home, holiday seasons, or personal lighting habits, reinforcing the role of lighting in emotional memory recall. This associative effect may contribute to a sense of normalcy and continuity in unfamiliar environments.

Descriptive Summary. Participants commonly described the experience with words such as "calm," "warm," "comforting," and "relaxing." These descriptors align with emotional relief, spatial warmth, and mental decompression. One participant expressed dissatisfaction using a more abstract phrase ("dark red circle"), indicating subjective variance in emotional interpretation.

Both Participant 3 and Participant 4 referred explicitly to the feeling of home when describing their experience with the colorful lighting in Casa España. Participant 3 noted that the warm, layered light felt *"very familiar – almost like something I would have in my own home,"* while Participant 4 stated simply, *"I felt more relaxed and at home."* These responses highlight how sensory elements like lighting can powerfully evoke emotional memories and foster a sense of familiarity in otherwise unfamiliar and harsh environments like Antarctica [15].

This small but diverse participant group demonstrates the significant emotional and psychological impact that ambient, colorful lighting can have in isolated environments. For most, the lighting transformed the perception of space and offered moments of emotional grounding and social signaling. While individual preferences varied, the overall findings support the hypothesis that customizable, mood-responsive lighting can serve as a low-tech intervention to improve well-being in extreme, confined settings such as Antarctic bases – and potentially, future space habitats.

c. Uses of Colourful Lighting Following the Intervention

Following the departure of the researcher from the St. Kliment Ohridski Antarctic Base, follow-up documentation and photographic material provided by the base personnel revealed a notable continuation – and intensification – of the use of colorful lighting in daily life. The two portable lighting devices previously used in the experimental phase – the RGB Sunset LED lamp (left at the base by the researcher) and the RGB "disco" lamp (already available on-site) – were both regularly utilized after the conclusion of the formal study.

A key shift in lighting use occurred in the Blue Container, which, over time, was transformed by the inhabitants into an informal social space. Both portable lamps were used frequently in this area to create an atmosphere conducive to social interaction and relaxation (Figure 12b). Unlike the sporadic or event-based use of colorful lighting prior to the intervention, its use in the Blue Container became regular and intentional, serving as a tool for enhancing the emotional quality of routine communal gatherings.

Another notable development took place in the New Laboratory Building, which became fully operational following the completion of interior works. Occasionally, the space hosted small group gatherings aimed at entertainment and stress relief. These gatherings often included the use of entertainment equipment such as a ping-pong table and a foosball table. While the colorful lighting was not initially used during the gaming sessions themselves, it was frequently activated as participants remained in the space into the evening hours (Figure 15). Thus, the RGB lamps once again accompanied social and leisure activities, reinforcing their emerging association with emotional decompression and collective well-being.

Notably, the personnel actively chose to move the portable lamps between different buildings to support these gatherings. This behavior indicates a clear demand for flexible, transportable lighting elements capable of adapting to changing spatial and social contexts. It also suggests that the value of colorful lighting extended beyond festive decoration into a consistent strategy for improving group morale [10] and ambient comfort.

Overall, this post-intervention use reflects a shift in lighting culture within the base: colorful lighting was no longer reserved for rare, celebratory moments but became a recurring feature of everyday socialization [10, 3]. This evolution supports the hypothesis that once introduced, non-traditional lighting solutions can organically become embedded in communal life, meeting psychological and emotional needs in confined, isolated environments [10].

8 Suggestions & Improvements

Participants in the first phase of the study suggested several improvements to enhance lighting conditions across the base. Many emphasized the need for better task lighting, calling for brighter, more focused illumination at workstations and during scientific activities, rather than relying solely on diffuse ambient light. Softer, warmer lighting in the evening was also recommended to promote relaxation and facilitate rest. Additionally, improved daylight simulation was proposed as a way to support circadian rhythm regulation and healthier sleep-wake cycles. Several participants highlighted the importance of integrating energy-efficient lighting solutions to align with broader sustainability goals. Finally, there was a widespread desire for user control over lighting – specifically through dimming features and adjustable color temperatures – allowing users to tailor the environment to specific tasks or personal comfort.

In the second phase of the study, which focused on the emotional and experiential impact of colourful lighting in Casa España, suggestions centered on adaptability and personalization. The importance of cultivating a sense of home in such settings cannot be overstated – it serves as a buffer against the psychological effects of isolation and monotony, promotes evening relaxation by creating a soothing atmosphere, and supports emotional regulation and resilience [7, 16]. Especially in environments with extreme daylight cycles and limited personal space, designing spaces that create emotional experiences [26] that evoke warmth, comfort, and homeliness can significantly ease adaptation and contribute to overall mental well-being.

While most participants reported positive emotional effects, such as increased relaxation, improved mood, and associations with home or leisure, the diversity of responses underscored the need for customizable lighting strategies that accommodate varying individual preferences. Additionally, post-intervention observations revealed a strong user-driven demand for portable, flexible lighting systems that could be relocated and repurposed across different social settings. These findings point to the importance of designing lighting not only for functional use but also as a dynamic emotional and social tool within isolated, communal environments [14].

9 Conclusions

The findings capture qualitative insights into what works well and actionable recommendations for lighting design improvements. They directly contribute to space exploration by providing actionable insights for creating resilient, adaptable lighting systems that prioritize astronaut well-being and operational efficiency in confined, isolated habitats like Mars bases or lunar stations [19]. This case study aims to bridge the gap between technical lighting systems and human experience, informing the development of intelligent, user-adaptive lighting for space analogues, polar missions, and long-duration extraterrestrial exploration.

a. Lessons Learned and Proposed Lighting Design Strategies

Findings from the Antarctic base study highlight the critical importance of customization in lighting design, particularly in extreme, confined environments. Participants consistently valued the ability to adjust brightness and color settings, emphasizing how such control enhanced emotional comfort and personal well-being. To address these challenges and support both well-being and operational efficiency, we propose a multi-layered, human-centered lighting strategy for use in environments like Antarctic stations and space analogues. Lighting systems should integrate functional, circadian, and mood-enhancing components [13] to meet varying emotional and cognitive needs throughout the day [5, 2]. Research confirms that nuanced combinations of illuminance and color temperature – especially when adapted to user preference – play a crucial role in emotional regulation and stress reduction [13]. In task-oriented areas, lighting must prioritize individual control, glare reduction, and directional adjustability, promoting visual comfort and minimizing stress during focused activities. Additionally, many participants called for better simulation of natural light cycles and more responsive lighting schemes, reflecting an awareness of circadian rhythms' long-term impact on health. Addressing these needs requires lighting systems that go beyond simple presets.

b. Colourful Lighting and Subjective Experience: Insights for Adaptive Design

The feedback on colourful lighting revealed a clear divergence in user preferences – some participants found it engaging and emotionally supportive, while others expressed a preference for more natural or neutral lighting conditions. Colorful lighting is beneficial for some; while not universally preferred, those who enjoy it also emphasize the importance of being able to customize their environment. For these users, the option to adjust lighting according to personal mood or activity contributed significantly to emotional comfort and a sense of control [25] within an otherwise rigid setting [5]. This finding reinforces the necessity for sensponsive lighting systems, which accommodate subjectivity by enabling real-time customization based on user behavior, preferences, and context [17]. By recognizing and adapting to individual differences, sensponsive design provides a resilient framework for improving well-being through personalized lighting strategies in challenging environments where sensory input is limited and highly impactful [18].

c. Social Spaces and the Feeling of Home

The Dining Hall emerged as a central node for communal well-being. Its combination of generous daylight, warm materials, and layered artificial lighting – including decorative string lights – created the only space perceived as "home-like" and emotionally comfortable. The presence of lighting scenarios (e.g., cozy evening ambiance) was subtle but powerful, reinforcing that social spaces benefit most from "home-like" [7, 16], atmospheric lighting that creates different emotional experiences [26] rather than purely functional setups. This distinction also points to a broader design need: social and workspaces should have different lighting atmospheres to support both focused tasks and mood enhancement. Task-oriented areas require clarity and concentration, while social spaces thrive with lighting that fosters warmth, relaxation, and informal interaction. This highlights the importance of designing common areas that prioritize emotional comfort, with lighting that supports the informal, restorative, and social functions of these spaces [3] – crucial in both Antarctic and space environments.

d. Novelty and Hypotheses for Further Investigation

The novelty of this study lies in its focus on user-driven adaptations and emotional responses to ambient lighting in a polar base, drawing parallels with future space habitat design. Our findings support the hypothesis that lighting plays a subconscious yet powerful role in emotional regulation, spatial identity, and social behaviour in isolated settings. This opens a valuable research direction: the integration of AI-powered sensponsive lighting systems in space analogues – systems that learn from behavioural patterns and adapt in real-time to emotional and contextual cues. These would go beyond circadian support to enable true personalization and dynamic atmosphere modulation, even in standardized environments.

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MUSE: Designing Immersive Virtual Realities for Spaceflight UX Research

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Abstract

Virtual reality (VR) provides unique opportunities for assessing early spacecraft design and usability by employing human-centered narrative and scenario-driven design methods. This paper details a narrative-focused VR simulation of a speculative spaceflight scenario, emphasizing narrative techniques for enhancing user immersion and user testing in evaluating operational usability aspects inside a spacecraft capsule. We designed a Modular User-centric Spaceflight Experience (MUSE) including a spacecraft capsule design and virtual mission scenario based on the findings and suggestions in Human Inspirator Co-Engineering (HICE) study. Results from user testing with MUSE underline the effectiveness and opportunities of narrative scenarios in early UX- evaluations in improving experience flow, operational understanding and user engagement. At the same time there remains several questions in defining best methodology to measure users insight and action motivation born from narrative immersion with the VR- experience.

2012 ACM Subject Classification Human-centered computing → Virtual reality; Human-centered computing → Usability testing; Human-centered computing → Scenario-based design; Human-centered computing → User centered design

Keywords and phrases Virtual Reality, Spaceflight Simulation, Narrative Design, Game Design, Scenario Design, Immersive Experience

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1 Introduction

Virtual Reality (VR) and Extended Reality (XR) technologies have increasingly become essential tools in astronaut and space operations training, primarily due to their flexibility, cost efficiency, and immersive capabilities [19, 18, 2, 3, 10]. This versatility means that VR can address particular training needs, such as the execution of operational activity and manipulation of machines. An emerging trend identifies that providing a user with immersive environments and using narrative capabilities within these environments provides a much deeper emotional connection and action-readiness through dramatic or structured storytelling pacing. [8, 21, 4]. Developing holistic narrative immersion experiences provides notable advantages for early mission design by leveraging VR environments to improve user interfaces and user experience, especially regarding scenario realism, intuitive decision-making, and creativity enhancement. A deeper immersion with a virtual experience is found to offer cognitive benefits to the user that support intuitive decision-making and engage creativity [5, 17, 11]. The research on Modular User-centric Spaceflight Experience (MUSE) builds


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upon the existing research carried out at the European Astronaut Centre (EAC) on immersive virtual operations [19, 18] and expands the horizon of immersive virtual experiences into a mission onboard a small speculative crewed spacecraft. This was a development opportunity identified by ESA's Human Inspirator Co-Engineering (HICE) study. MUSE addresses the previously identified narrative human-centered opportunities of VR by integrating a narrative-driven design framework into a modular project structure, combined with user testing done during simulated capsule docking operations. By utilizing immersive frameworks to enhance the realism and effectiveness of operational training scenarios, we gathered insight-based user feedback to understand better how game engine flexibility serves experience immersion and narrative structure, and may help or hinder operational awareness during a simulated mission in a spacecraft capsule environment [15, 25, 13]. Based on these goals, the study addresses two core research questions. Firstly, how can immersive narrative-based VR experiences be designed to foster user interest and engagement with human spaceflight missions to LEO and lunar orbit? Secondly, in what ways can a speculative VR simulation, based on current mission knowledge, be used to anticipate and inform the design of future spacecraft operations?

2 Related Work and Theoretical Foundations

2.1 VR/XR Uses in Spaceflight Training

Virtual Reality (VR) and Extended Reality (XR) technologies are increasingly prominent tools in astronaut training and space mission preparation, primarily due to their development flexibility, reduced physical risks to testers, and cost efficiency at large. Traditional astronaut training methods, such as analogue environments, neutral buoyancy pools, and parabolic flights remain invaluable, but they are also increasingly resource-intensive, may require additional specific training, entail physical risks, and may have limitations concerning repeatability and scenario realism. In contrast, VR and XR offer highly controlled and reproducible simulation environments that facilitate extensive rehearsal of operational tasks with significantly lower resource demands [19, 3]. There remain several challenges, too, regarding the use of VR for training, particularly aspects of technology constraints, user comfort and user interface design needs [16].

With these challenges and opportunities in mind, VR and XR technologies are studied to anticipate their potential to support human and robotic mission training in the field of space systems development. Immersive technologies, such as immersive VR experiences, have been identified for their opportunity to support task-focused training and machine operation, largely focused on areas of skill development and performing specific procedural tasks that support memorization and recall [12]. Other examples of immersive VR use include engaging with the user in a more personalized level in areas of customized training, team building, inspiration and motivation. Various studies also demonstrate VR environments' potential for design and evaluation of usability [10, 19, 18, 8]. The need for immersive enrichment in VR-based scenario training has been clearly identified within European Space Agency's (ESA) operational contexts, extensively used for both astronaut training and as an aspects of operational ergonomics during early mission design. For example, in a case study on EL3 lander done at the European Astronaut Center (EAC) by Nilsson et al (2022) the aspects of structured timelines and scenario-based interaction in benefit of enhancing immersion and crafting meaningful scenarios are highlighted. Structuring the VR experience narrative for immersive realism was seen crucial for the value of the experience [19].

Narrative elements in VR experiences are more commonly employed in VR games and cultural visual experiences, where they can host aspects of psychological realism, storytelling, and emotionally engaging action [11, 17]. Recent research indicates that immersion within narrative-rich virtual experiences significantly enhances user creativity and the capacity for insight-based problem-solving by evoking awe and promoting creative problem-solving through deeper cognitive and emotional engagement [17, 11, 25, 14].

2.2 The Key Advantages of Using Narrative and Scenario-Driven Design in Game Design

Game design theory and narrative design methodologies offer useful tools for structuring immersive virtual reality (VR) environments, particularly in contexts of training new tasks and speculative scenario development. Frameworks like Freytag's Pyramid and the Hero's Journey, are commonly used in interactive media and serve not only as storytelling devices but also as models for guiding emotional pacing, cognitive engagement, and decision-making within a simulated context [21, 4, 1]. These narrative structures can be aligned with Csikszentmihalyi's theory of Flow, where users experience a high level of focus and involvement when the balance between task difficulty and user skill is carefully managed [7]. When integrated into VR simulations, these frameworks can support emotional involvement in the simulated world and promote intuitive responses to emerging events. This aligns with Carpenter's description of insight as a moment of sudden understanding born from unconscious cognitive processing, contributing to adaptive thinking and creative way to solve problems [5].

From a user interface (UI) and user experience (UX) perspective, narrative immersion offers several practical benefits. It can reduce cognitive load, support attentional focus, and enable users to respond more effectively in high-pressure operational contexts [2, 23]. Narrative components in user interfaces may also help with memory retention and emotional relevance, which can be especially helpful in training settings where task repetition alone may not address all learning goals. By applying narrative-oriented methods from game design, developers can create virtual training tools that foster adaptability, creativity, and engagement. These qualities are relevant for astronaut task and mission preparation, particularly in complex scenarios involving different tasks [15, 25, 19]. Including game design methodology more centrally in design of VR experiences can further advance the development of systematic design practices that link performance requirements of these experiences with the cognitive and emotional dimensions of users in space environments.

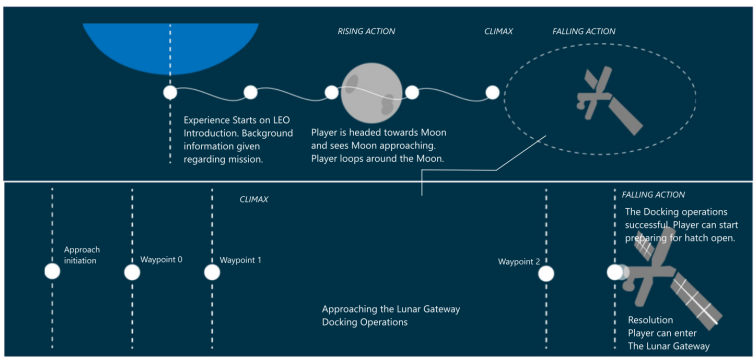

Figure 1 Mission steps structured to support a narratively engaging VR experience.

3 Methodology

3.1 Scenario Ideation and Narrative Development Techniques

The scenario developed for this research adopted iterative and participatory design methods, explicitly structured around the well-established narrative framework called Freytag's Pyramid, consisting of clearly defined phases including a rising action, climax and falling action, to create a dramatic and comprehensible narrative arc. This structured approach (see Fig. 1) facilitated operational realism of having a structured phasing to the mission and immersive storytelling by providing users with emotional and cognitive pacing for a deeper immersion and enhanced user engagement throughout the experience [21, 4].

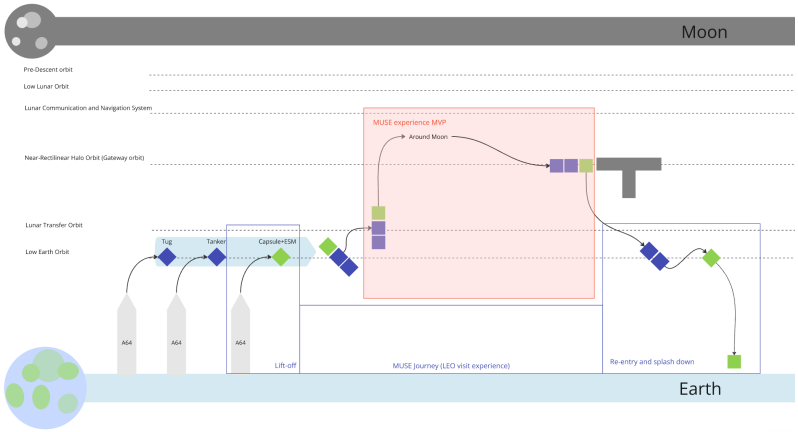

Figure 2 Planning the mission steps as part of wider mission description.

Based on ESA's Human Inspirator Co-Engineering (HICE) study, the MUSE VR experience aimed to assess the technical and programmatic feasibility of extended human missions, including existing and new opportunities to Low Earth Orbit (LEO), Lunar Gateway station, and the lunar surface. This initiative offered multiple realistic use-cases, of which one scenario was adopted as the narrative framework for this research (see Fig. 2). Following the recommendations and preliminary findings of the HICE study, the scenario closely adhered to the identified challenges and opportunities of crewed missions starting from LEO and culminating in docking operations at the Lunar Gateway station, including astronaut transfer from the spacecraft to the station. The architectural elements of the spacecraft, particularly its capsule environment and its configurations, were likewise informed by the HICE study outcomes, ensuring that the virtual experience maintained authenticity and relevance to current real-world considerations while offering valuable insights into user interface (UI) and user experience (UX) design.

Given that mission timelines and specific operational details within the HICE study remain speculative, the scenario and spacecraft design required considerable adaptability to consider the needs of several stakeholders and technology opportunities. Thus, a modularization strategy was adopted (see Fig. 3). Leveraging the flexibility provided by Unreal Engine 5.3. VR development pipeline the modularity enabled interchangeable scenario components, and 3D model configurations, addressing evolving knowledge and iterative refinements throughout development. This approach allowed scenario elements such as spacecraft modules and narrative mission parts to be quickly adapted or replaced as new insights emerged, enhancing responsiveness to changing scenario understanding and facilitating future scalability and refinements in the training experience [6].

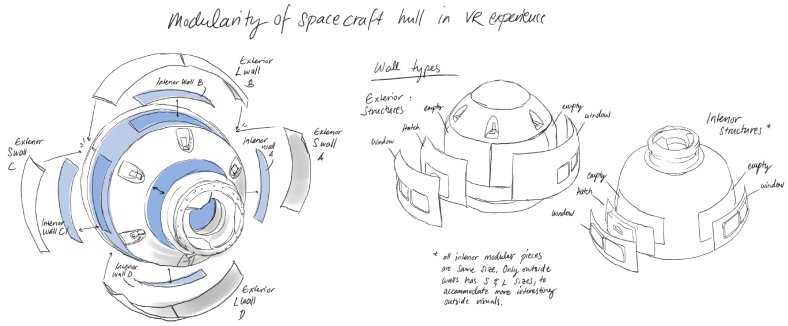

Figure 3 Capsule wall modularity plan for 3D parts.

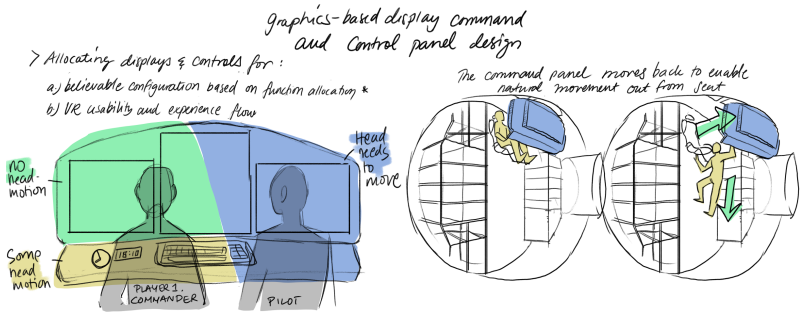

Figure 4 Capsule interior planning for VR user comfort and mission realism.

3.2 Speculative Mission Scenario and Spacecraft Design Rationale

While inspired by existing and conceptual spacecraft designs, such as the Orion and Crew Dragon capsules, the spacecraft developed for the virtual scenario in MUSE incorporated further findings from the HICE study, such as the earlier mentioned need for adaptability to evolving mission design requirements. The design aimed to balance narrative-driven immersion with operational authenticity by managing constraints like spacecraft scale, visual fidelity, and internal functionality through strategic planning of interchangeable and adjustable parts (see Fig. 3 and Fig. 5). This modular methodology aligns with established best practices from previous immersive virtual experiences developed at ESA, where structural flexibility and adaptability have supported ongoing iteration for mission prototyping and user testing [19, 2].

In addition to the physical and spatial design, narrative immersion was further grounded through the integration of a voice-loop system modeled on real docking procedures with Crew Dragon spacecraft and the International Space Station (ISS). Audio material was referenced from public Apollo mission archives and supplemented by live dialogue data recorded during a recent Crew Dragon docking operations. This audio was simplified, processed and adapted into a three-way communication structure that reflects the style and content of authentic operational voice loops. By embedding this system into the VR narrative, the experience preserved operational realism, for example in simulating realistic challenges in docking operations, while introducing new narrative elements, effectively bridging fictional scenario development with authentic astronaut communication dynamics.

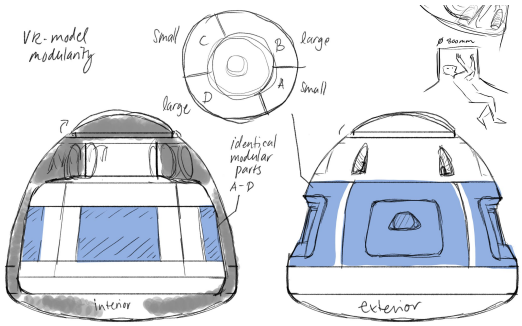

Figure 5 Interchangeable modular pieces part of the capsule hull.

Special emphasis was placed on the spacecraft capsule design, carefully refining both external geometry and internal layouts to align closely with the HICE study's identified goals, including habitability, ergonomics, and operational efficiency. Modularity of 3D parts ensured that the spacecraft interior and scenario interactions could remain dynamically aligned with evolving mission requirements and new ergonomic insights as they arose through ongoing research and user feedback. Modular design allows for targeted testing and training scenarios, offering insights into user interaction design, mission planning, and decision-making effectiveness across diverse user groups, from mission planners to astronauts [6].

Interior design specifically emphasized immersive user experiences, aligning narrative interactions with functional and ergonomic realities of the spacecraft environment (see Fig. 4), such as identified division of onboard workspace intended for the VR user [20]. Environmental storytelling techniques, such as integrating a narrator's voice, was added to enhance intuitive decision-making processes. This narrative approach aimed to complement traditional heuristic-based training methods by actively facilitating intuitive, insight-driven strategies among users, and fostering deeper cognitive engagement and situational awareness [5, 11, 10].

4 Experimental Setup and Evaluation Methods

The immersive narrative-driven VR experience that was created for the speculative mission served as an experimental setup for gathering user feedback. In particular we wanted to gather data of the user experience during the spaceflight scenario, including the more task oriented docking operations. An evaluation framework was created to serve the different aspects of the experience to retrieve quantitative and qualitative research data.

4.1 Narrative and Situational Scenario Evaluation Methodology

The evaluation framework combined semi-structured quantitative assessments and qualitative exploratory approaches, employing think-aloud protocols, observational methods, structured surveys, and more detailed qualitative interviews regarding the overall experience.

Our first research question required understanding both when and how much the user was engaged with the experience. We combined in our methodology the monitoring of users movements and engagement activity to understand cognitive investment at any given situation. Similar technique has been described for example in research by Sun et al. [24], to observe how users physically engaged with critical scenario events. User behaviors, such as turning towards audio cues, manipulating interface elements, or physically leaning into tasks, were logged and cross-referenced with quantitative post-experience assessment. Makransky et

al. (2019) emphasize the value of combining self-report measures (e.g., enjoyment, motivation, and self-efficacy) with behavioral transfer tests to comprehensively evaluate immersive VR training [14]. Emphasis was therefor placed on capturing intuitive decision-making processes in the moment and conducting an after testing qualitative interview [23, 16, 19].

To explore our second research question, the VR simulation incorporated a simplified Situation Awareness Global Assessment Technique (SAGAT) to assess user responses to modular capsule environments. In particular this was done by measuring user responsiveness to operational, mostly audio cues through timed reactions, underlining how narrative-driven scenarios influenced intuitive decision-making during operation. Furthermore a situational awareness rating technique was used as a quantitative method and self assessment after the testing, keeping in mind that self-rating after testing is subject to for example poor recall rates [6, 9, 22].

These methods enabled us to look at immersion patterns and align user reactions with narrative turning points within the experience. This UX assessment strategy was the foundation for exploring cognitive processes like intuitive decision-making and situational awareness in narrative-driven VR scenarios.

4.2 User Testing Procedures

The participants were selected with a view to having a high degree of role variability as stakeholders for the MUSE experience. Before the actual testing the users were identified for their potential stakeholder role and experience of using VR, and invited individually into the testing session. Upon entering the testing session the user was greeted and offered a brief overlook into the upcoming testing, and given a quick introduction to using the VR-headset and hand controls before donning the headset. Users were also informed about the general narrative goal of the experience, flying onboard a small spacecraft to the Lunar Gateway and being tested for situational awareness during docking operations. Similarly to the testing setup done by Nilsson et al. for the EL3 lander, the users were encouraged to verbalize their experiences, and reasoning during the docking operations [19]. After the testing session, which took about 10-15 minutes, depending on the users curiosity to explore the experience longer, the users were asked to fill in two questionnaires right after the testing, and further verbalize their thoughts in a general manner regarding the two research goals we had.

The user testing involved surveys, observational protocols, and emotional and physical response tracking to help heuristic evaluation and apply a multi-level assessment [23, 16, 8]. Collecting such varied data however posed a challenge of how to combine the data in a meaningful way to offer insight in the best way. The testing did not include tools, such as eye or position tracking, or measure precise moment when users pressed for example a button. The test included two monitors who marked the information regarding these events manually. The users were instructed before the testing of the correct way to react during the situational awareness test to tick a box (press a button) in the VR interface on the capsules command panel. Outside the docking operations the users were monitored also for their other physical reactivity, such as naturally occurring reactions towards narrative elements when there was no particular voiced command to interact with the Command Panel.

4.3 Findings: Usability, Immersion, and Emotional Engagement

The experience was structured into sequential narrative stages: beginning with mission preparations in Low Earth Orbit (LEO), followed by lunar flyby transit, and concluding with approach, docking operations and entering the Lunar Gateway. While one phase

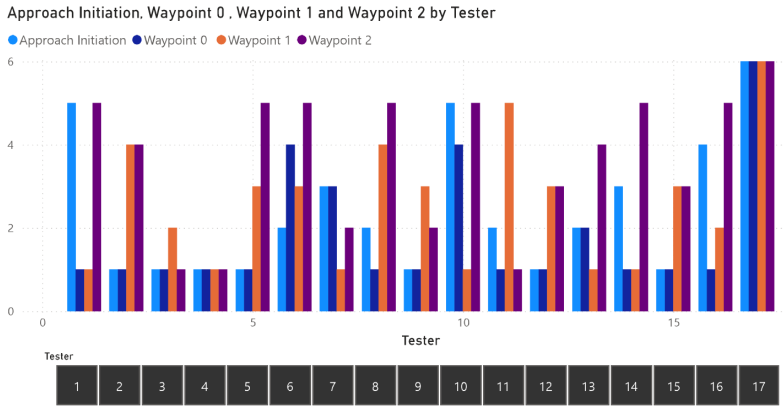

Figure 6 Assessment of testers reaction speed and certainty of action during a Situational Awareness testing of docking operations.

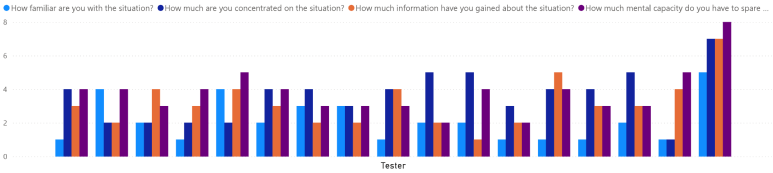

Figure 7 Quantitative self assessment of testers situational awareness and emotional engagement after the experience.

was focused on situational awareness and explicitly incorporated a task-based cognitive evaluation (see Fig. 6 and Fig. 7), user feedback and observations across the entire experience consistently revealed high levels of emotional and cognitive engagement. In our assessment of the outcomes it seemed that the relative experience of an individual dealing with similar operational scenarios correlated with faster and more precise reaction times during docking operations. Participants described a strong sense of excitement and curiosity throughout, particularly in quieter moments before and after operational tasks. Many explored the interior environment of the capsule early to the experience, moving between seats and physically leaning toward the windows to observe landmarks passing by the window such as Earth, the Moon, and the Gateway station (see Fig. 8). These patterns mirror findings by Sun et al. [24], who demonstrated that heightened movement within VR scenarios correlates with stronger presence and task engagement. While functional interaction was concentrated around the command panel due to its central role in the experience management, user movement patterns also indicated spontaneous interest in non-operational elements of the environment. However, participants generally avoided interacting with passive props like cargo racks, indicating selective engagement shaped by narrative relevance. These behavioral insights align with Makransky et al.'s [14] findings on immersive learning, which emphasize that immersive VR environments are most effective when users are emotionally engaged and immersed, even if not all elements contribute to learning actively. In our study, physical engagement often increased in anticipation of narrative turning points, reinforcing the important role of storytelling in guiding embodied presence. This also resonates with Carpenter's work on insight and creative cognition, which highlights that intuitive realizations of information can arise during periods of passive observation or cognitive rest [5]. These moments of exploration and reflective curiosity may thus support the conditions necessary for intuitive insight, underscoring the value of designing narrative structures that allow for such psychological incubation.



Figure 8 A view near to the Commander's seat where the player would be seated during part of the mission.

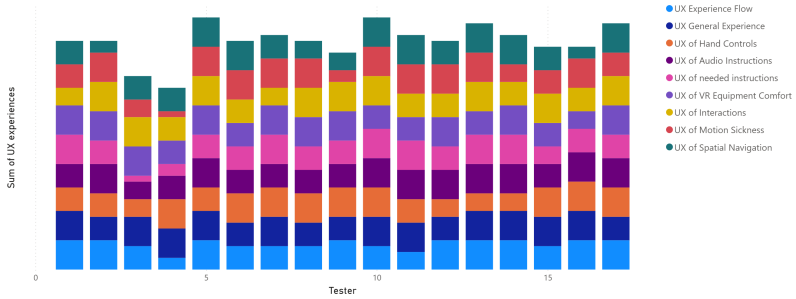

Figure 9 Summarizing the overall User Experience the testers reported right after testing.

Despite the overall success in immersion and reports of generally good user experience, several usability concerns emerged during the whole length of the experience (see Fig. 9). Participants occasionally struggled to return to optimal viewing positions after moving around the capsule (spatial navigation issue), sometimes leading to confusion or diminished visibility of essential UI elements like the mission timeline or command panel. During the situational awareness testing, some users inadvertently marked mission steps as complete prematurely. These incidents were often due to misunderstandings of audio cues (audio instruction issue), over-anticipation of events to come, or accidental controller contact with the user interface in the limited capsule space represented in the VR experience around them. Such errors emphasize the importance of multi-modal narrative design, combining clear audio cues, visual reinforcement, and spatial UI alignment to support reliable user interaction. Participants also reported cases of immersion being abruptly disrupted by external environmental noises, highlighting the fragile nature of deep presence and the need for consistent sensory control in high-fidelity training simulations, especially for experiences that rely on audio ques and concentrating on listening activities [8, 19, 2, 25]. Importantly, instances of intuitive decision-making were observed, especially when users acted under uncertainty, when they were either misinterpreting technical terminology in the audio loop or attempting to multitask. These moments, although sometimes resulting in operational errors, are informative for understanding how narrative and scenario structure influence not only task accuracy but also individual intuitive cognitive processing. Awareness of such insight-based behavior complements earlier findings by Makransky et al. [14], who advocate for multi-level assessments for VR use. In narrative VR contexts, this represents an insight towards testing individual situational adaptation in both active and passive stages of the experience, rather than merely during the actual mission procedure.

5 Discussion: Narrative's Role in VR User Experience

According to user feedback, the narrative-driven design significantly enhanced the overall user experience, influencing emotional immersion, intuitive decision-making, and creativity during scenario interactions. Users described experiencing emotionally charged moments like excitement, curiosity, or concern especially when embedded in key scenario transitions, such as approaching the Lunar Gateway and listening to mission-critical voice loops during docking. These reactions support the idea that a coherent narrative structure strengthens engagement by offering emotionally resonant context and purpose.

However, the immersive quality was vulnerable to disruption. Breaks in immersion were commonly reported when users encountered either unclear or overly simplistic UI interactions, audio misalignments, or external distractions (real-world noise bleeding into the experience). Participants reported that in such moments, immersion became more difficult, highlighting the importance of narrative coherence supported by user comfort and consistent sensory input [8, 19, 2, 25].

A particularly notable theme in post-experience interviews was the difficulty many users had articulating why the experience felt meaningful or immersive. While most users reported a strong sense of presence and enjoyment, they often struggled to explain the cognitive processes that led to those impressions. This observation aligns with Carpenter's insights into intuitive cognition: people often cannot consciously retrace the steps behind intuitive decisions or insight moments due to their unconscious nature [5].

This raises a pressing methodological challenge for further VR research on understanding immersion: if users' compelling reactions are driven by subconscious, intuitive processes, how can we best observe and interpret them? Future research must grapple with this question, especially when evaluating how immersive storytelling influences cognition in operational scenarios. A best way forward may be drawing on Makransky et al. [14] research data advocating for development of multi-level assessments – combining behavioral tracking, task performance, and motivational responses as an effective way to assess how deeply users internalize and respond to immersive environments.

Our findings echo users often displaying physical behaviors such as orienting toward the windows, leaning toward control panel, or exploring the capsule interior that reflect engagement with the narrative, even in the absence of active task demands. This suggests that narrative-driven immersion on its own can provoke embodied presence that supports user insight and situational adaptation. Instead of limiting operational evaluations to procedural correctness, narrative immersion provides fertile ground for observing how users adapt creatively or intuitively in speculative spaceflight or other future space mission scenarios.

6 Practical Implications and Future Research

This research underscores the growing value of narrative-driven immersive VR scenarios in crew and astronaut training and early-stage UX/UI exploration for spaceflight. Beyond operational task rehearsal, these experiences demonstrate how storytelling and structured immersion foster deeper emotional involvement, enhance intuitive adaptability, and reinforce situational awareness. These are key skills in unpredictable, high-stakes environments such as long-duration space missions.

Feedback gathered from extended testings, both with research participants and at later point in public outreach events where the VR experience was presented indicates strong potential for educational deployment. The emotionally engaging nature of narrative VR makes it suitable not only for astronaut training but also for public engagement and science

communication. Story-rich scenarios appear to increase layperson understanding of complex mission architectures and human factors on a basic level in spaceflight, echoing findings by Murray-Smith et al. [15] and Nilsson et al. [18].

Future studies should aim to develop robust methodologies for capturing subconscious or intuitive reactions during immersive experiences. This might include combining movement tracking, emotion recognition, and self-assessment tools, and adapting cognitive science frameworks to interpret spontaneous, insight-based decisions. Such methods would offer valuable new ways to assess non-obvious cognitive processes and to evaluate UI designs intended for fluid, intuitive use in spaceflight systems.

7 Conclusion

Narrative-driven immersive VR emerges as a promising methodology for supporting human-centered UX design and training in speculative spaceflight contexts. Our findings show that immersive storytelling not only fosters emotional engagement but also encourages intuitive decision-making and embodied user presence.

By embedding users within a coherent and emotionally resonant story arc, narrative VR enables researchers and designers to observe complex cognitive and behavioral dynamics, including user intuition, situational adaptability, and motivational engagement. The unconscious nature of insight formation further underlines the need for innovative assessment tools capable of capturing these cognitive responses.

Ultimately, narrative-driven VR holds strong potential to enhance existing training tools for astronaut preparedness, support mapping adaptable thinking, and advance UI and UX design for mission-critical systems. Its utility extends beyond operational rehearsal to science communication, outreach, and scenario-based research. As new mission architectures, space ecosystem stakeholders and deep-space exploration strategies evolve, VR environments that mirror complex cognitive and emotional realities will become essential to preparing humans for space.

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Advancing Intelligent Personal Assistants for Human Spaceflight

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Abstract

The Artemis program and upcoming missions to Mars mark a new era of human space exploration that will require new tools to support astronaut autonomy in the absence of real-time communication with Earth. This paper investigates the role of voice-based intelligent personal assistants (IPAs) in future crewed space missions. Through semi-structured interviews with astronauts (n=3) and spaceflight experts (n=12), we identify key user-centered design requirements for IPAs in this uniquely constrained and safety-critical environment. Our thematic analysis reveals core requirements for flexibility, reliability, offline capability, and multimodal interaction. Drawing on these findings, we outline design guidelines for next-generation IPAs and discuss how technologies such as retrieval-augmented generation (RAG), knowledge graphs, and augmented reality should be combined to support flexible, reliable, and multimodal IPAs for future human spaceflight missions.

2012 ACM Subject Classification Human-centered computing → Empirical studies in HCI; Computing methodologies → Intelligent agents

Keywords and phrases Conversational Assistant, Intelligent Personal Assistant, Artificial Intelligence, Astronaut, Human Spaceflight, Generative Pre-Trained Transformer (GPT), Retrieval Augmented Generation (RAG), Knowledge Graphs, Augmented Reality, Voice Assistant, Long Duration Spaceflight

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1 Introduction

Amidst a surging interest in human space exploration, ambitious programmes aiming to establish a sustained human presence on the Moon are now underway, with crewed missions to Mars projected to follow soon after [43]. The nature of these missions represents a shift not only in distance and duration, but also in the complexity and level of autonomy required from astronauts.

Historically, astronauts operating in Low Earth Orbit or on the lunar surface relied on relatively rudimentary tools such as printed checklists while benefiting from uninterrupted, real-time supervision by ground control [33, 31, 18, 28, 21]. In contrast, future missions will involve operations of unprecedented complexity, including the assembly of surface infrastructure and in-situ resource utilisation, placing significant cognitive and physical demands on the crew.

These challenges are further increased by communication constraints. The Artemis lunar programme, for example, is targeting the Moon's south pole, an area prone to recurring blackouts due to topographical shadowing and orbital libration, making reliable contact with

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Earth difficult [48, 19, 8, 17, 23]. Similarly, during future Mars missions, astronauts will experience latencies of up to 42 minutes in round-trip communication with Earth [24]. In such contexts, autonomy is not a supplementary feature but a mission-critical necessity.

To support this autonomy, voice-based intelligent personal assistants (IPAs) are attracting growing attention in the space domain. These systems promise hands-free, naturalistic interaction and could serve as intermediaries between astronauts and a wide range of operational systems. Thanks to advances in artificial intelligence, IPAs may be able to provide assistance even in dynamic or time-sensitive scenarios.

Prototypes, such as METIS [6], which supports ground control, CIMON tested on the International Space Station (ISS) [13] or CORE [5], designed to aid astronauts during long-term missions, point in this direction. Yet, their development has largely prioritised technological feasibility, with limited focus on their human-centered aspects, such as usability and other user requirements in the context of future human spaceflight [6].

In this work, we examine IPAs not merely as retrieval interfaces but as collaborative systems supporting astronaut autonomy under constrained and safety-critical conditions. The study is guided by the following research question: *What are the core user-centered requirements for IPAs in future space missions beyond Low Earth Orbit?*. Drawing on semi-structured interviews with astronauts (n=3) and domain experts (n=12), we explore the core requirements for IPAs in future space missions. Our findings point toward the need for flexible, reliable, and locally deployable (offline) multimodal systems capable of adapting to evolving operational demands.

In addressing the central research question, we present the following contributions: 1) A qualitative analysis of IPA requirements derived from interviews with astronauts and space experts. 2) The identification of four central themes: flexibility, reliability, offline availability, and multimodal feedback, each contextualised within specific operational scenarios, and lastly 3) initial directions on how to target each theme from a technical standpoint, using knowledge graphs (KGs), Retrieval Augmented Generation (RAG), and Augmented Reality (AR) cues.

2 Related Work

Over the past decade, IPAs have become increasingly relevant to space exploration, particularly as voice interfaces mature and onboard computing capabilities improve. Early deployments in low Earth orbit, such as CIMON (see Figure 1), have laid the groundwork for their potential use in future missions.

CIMON, launched to the International Space Station in 2018, was one of the first artificial intelligence-powered assistants tested in space [13]. Based on IBM Watson, it supported basic voice interaction and experiment assistance but relied on internet connectivity and could not function autonomously. Its successor, CIMON 2, included minor improvements such as facial recognition and sentiment (i.e., analysis of emotional tone) detection, but remained rooted in narrow artificial intelligence principles, offering limited adaptability or learning capabilities [38].

More recently, Amazon's Alexa was integrated into the Artemis I mission as part of a technology demonstration, signaling commercial interest in extending voice assistants to the space domain [1]. Similarly, the AI4U assistant, developed using reinforcement learning, is being tested under Mars analogue conditions with the aim of future International Space Station deployment [42, 34, 45]. While promising, AI4U requires extensive pre-training and has yet to be validated in real operational settings.



Figure 1 CIMON, an early example of an intelligent personal assistant deployed aboard the International Space Station. It served as a proof of concept for voice interaction in microgravity but was limited by its reliance on narrow AI and Earth-based processing.

Other approaches, such as METIS [6] and CORE [5], integrate RAG and KG technologies to enable more structured and reliable information delivery. These systems represent a departure from earlier rule-based assistants and reflect growing interest in generative models. However, existing work has largely focused on feasibility rather than usability. Questions of trust, explainability, and interaction under communication constraints remain underexplored.

Within the human-computer interaction community, there is a growing recognition of the need for more user-centered approaches to artificial intelligence design, particularly in safety-critical or resource-constrained environments. Prior work in aviation, healthcare, and remote operations has shown that trust, explainability, and multimodal feedback are essential to support effective human-AI collaboration [27]. However, these findings have yet to be fully applied to the spaceflight context, where procedural rigidity, environmental constraints, and isolation introduce additional design challenges.

With this study, we aim to help lay the groundwork for closing this gap. Through interviews with astronauts and domain experts, we examine IPA design not only as a technical challenge but as a human-centered one. In doing so, we contribute a perspective grounded in astronaut experience and operational realities, offering a foundation for the next generation of IPA systems in human spaceflight.

3 Methodology

3.1 Participants

For this study on IPAs for future human spaceflight missions to the ISS, Moon, and beyond, we selectively invited experts from a range of disciplines related to space operations and planetary exploration. Participants were recruited via purposive sampling based on their expertise in astronaut operations, training, or space technology development. Invitations were extended through professional networks, institutional affiliations, and referrals. The

final sample included 15 domain experts, among them 3 active astronauts with a combined total of approximately 900 days in space and over 20 hours of extravehicular activity (EVA) on the ISS (see Table 1).

In addition to astronauts, the group included engineers with mission planning and crew training experience, instructors supporting astronaut training and EUROCOM operations, and scientists involved in lunar and Martian field studies. All participants reported prior use of conversational agents such as Alexa, Siri, Google Home, or ChatGPT, and several had direct experience with CIMON, the AI assistant deployed on the ISS.

Table 1 Summary of participant demographics. Areas of expertise are self-reported.

Role	Gender	Job Title	Area of Expertise
Astronaut 1	F	Astronaut	Human Spaceflight, EVA
Astronaut 2	M	Astronaut	Human Spaceflight, EVA
Astronaut 3	M	Astronaut	Human Spaceflight, EVA
Engineer 1	M	Aerospace Engineer	Aerospace Engineering, Astronaut Training
Engineer 2	F	Engineer	Human Factors and Ergonomics
Engineer 3	M	VR/AR Software Engineer	VR/AR Software Engineering
Engineer 4	M	In-Space Manufacturing Specialist	In-Space Manufacturing
Engineer 5	M	In-Space Manufacturing Specialist	In-Space Manufacturing
Instructor 1	M	Astronaut Training and Simulations Support	Training and Simulations of EVAs
Instructor 2	M	Astronaut Training and Simulations Support	Training and Simulations of EVAs
Instructor 3	F	Training and EUROCOM Specialist	Training and EUROCOM
Scientist 1	F	Research Fellow	Machine Learning
Scientist 2	M	Lunar Scientist	Lunar Science, LUNA Facility, Aerospace
Scientist 3	M	Physicist	Physics, EUROCOM Crew Support
Scientist 4	M	Space Radiation Shielding Specialist	Space Radiation Shielding

3.2 Procedure

Participants were invited to take part in semi-structured interviews conducted in a quiet room at our lab at the European Space Agency's European Astronaut Centre (ESA-EAC). All participants provided informed consent prior to the interviews. The interviews lasted around 30 minutes. A pre-formulated interview guide was used to ensure consistency across sessions, while still allowing room for follow-up questions and deeper exploration of interesting topics raised by the participants. We observed that thematic saturation was reached by the 13th interview, with no new themes emerging in the final two sessions. The interview questions focused on the following areas:

- *What are the essential requirements that IPAs must fulfill to be used in future space operations?*
- *What are the critical shortcomings of existing IPAs, such as Alexa, Siri, Google Home, and CIMON, that could hinder their effectiveness in space operations?*
- *Do the requirements for IPAs vary between missions to the ISS, the Moon, Mars, or extended-duration spaceflight? If so, how?*

The interview guide was based on previous work in human-computer interaction, IPAs, and extreme environment operations (e.g., spaceflight, military). It was reviewed by two domain experts to ensure relevance and clarity. When participants raised unanticipated points, we asked follow-up questions to explore those aspects in more detail.

All interviews were conducted by a member of the research team familiar with the topic of space systems and human-agent interaction, which helped establish rapport and contextual understanding. Each session was audio-recorded and transcribed verbatim by the research team.

3.3 Data Analysis

We conducted a thematic analysis following the six-phase approach described by Braun and Clarke (2006) [9]. This method was chosen for its flexibility and suitability in identifying patterns and meanings across qualitative datasets. The process included familiarization with the data, initial code generation, theme identification, theme review, theme definition and naming, and final report production.

Two researchers independently coded the transcripts using a manual approach (without software assistance). Code themes were initially developed inductively from the data, without relying on any pre-existing coding frame. After independent coding, the researchers met to compare their respective findings, resolve discrepancies through discussion, and consolidate them into a shared coding scheme. This collaborative process served as an informal approach to establishing inter-coder agreement, ensuring that themes were consistently and accurately represented.

Emergent themes were iteratively refined and synthesized into a coherent thematic structure that captured the key insights and challenges regarding the deployment of IPAs in human spaceflight contexts.

4 Qualitative Findings

4.1 Flexibility

The interviews highlighted the importance of flexibility in IPA systems, emphasizing the need for adaptability across a wide range of tasks and contexts. This included not only practical applications such as checklist completion, suit monitoring, and navigation, but also the ability to modulate behavior based on different scenarios, emergencies versus routine tasks, and user preferences. Participants repeatedly pointed out that IPAs should offer a degree of personalization and responsiveness to unforeseen situations.

Scientist 4 envisioned a system that supports dynamic adaptation: *"A personalized setup... that is also flexible depending on the activity."*

Instructor 2 framed adaptability in terms of learning from astronauts' training performance: *"If you know you will operate with someone, you will train with this person, spend some time with them, and adapt. At the moment, we're only adapting the way we're communicating with and treating astronauts. We don't adapt procedures, for example. But procedures could be adapted using AI. During the training it might learn: 'Hey, this crew member is always struggling with this one step.' So when the crew member reaches this step, they could be shown a video of him or her performing it during training. Operationally, that could be very useful."*

A recurring theme was the need for a flexible communication style. Participants wanted to be able to tell the assistant how to behave. **Engineer 4** noted that astronauts may prefer concise instructions: *"Not verbose, or like very quick."*

Instructor 3 reflected on the possibility of training the AI to adapt emotionally: *"Your Alexa you can also train to be more emotional or more rational. If you keep shouting at your Alexa and cursing at it, it also becomes very...[unfiendly]. But if you say 'Hey, how are you this morning?', then Alexa also starts responding in a more friendly, emotional, human kind of way."*

This personalization extended into entertainment and well-being. **Engineer 5** described the importance of tailoring the assistant's tone and content to the user's mood and context: *"It's super personal. Some people really love it if they get jokes every five minutes. Others just want military-style instructions, without being bothered by any side-talk. Some might find it useful if their heart rate is up and somebody plays classical music. But others might think, 'Stop this and let me work.' That's something the AI could do for you or offer you."*

While some participants were open to emotionally adaptive responses, many expressed discomfort with AI systems that mimic human behavior too closely. **Scientist 1** and **Engineer 4** raised concerns about systems attempting to simulate personalities or emotional intelligence without sufficient realism.

Scientist 1 shared: *"I always find it super creepy when you try to make something more human-like. You know, these kinds of things where it looks too close to being real, but the technology is not good enough. I think because AI is the only thing that, no matter what, is trained on a subset of data. Whereas a person can take in all the information, and it's also culture. It's not flexible."*

Engineer 4 recounted his experience simulating AI characters: *"My friend and I pretended to give our character to ChatGPT, but then you could always tell it was simulated. It wasn't real. I would find that unnerving. Unless the AI is extremely good at fooling me or really consistent in its answers, I would rather not have a personality. It needs to be consistent, or it takes away the immersion."*

Engineer 5 echoed this sentiment, preferring machine-like behavior over human mimicry: *"It would probably be a computer-style voice rather than pretending to be human. Right now, it is pretending to be human with feelings and emotions. If the AI knows you're stressed, it will change its voice level like a human would. That feels wrong to me. It reads my heart rate and talks to me calmly. But if I'm relaxed and it knows I'm an hour behind schedule, it talks differently again. That might feel wrong, although maybe with time, I would get used to it."*

Although a few participants valued social and emotional cues in voice interaction, the majority favored a more neutral, logical assistant, especially in high-stakes or emergency contexts. **Scientist 1** summarized this view: *"If you're actually in a life-threatening situation, you want precise answers. It's okay not to be joking around too much."*

Overall, participants emphasized that flexibility should not only address task support but also adapt to user preferences, emotional context, and operational demands. However, this flexibility should be implemented with care to avoid overstepping into unrealistic or unsettling human imitation.

4.2 Reliability

The importance of IPA's reliability consistently surfaced as another key theme in the interview study. Drawing from their first-hand experience with AI deployments such as CIMON aboard the ISS and commercial systems like Alexa or ChatGPT, many participants expressed skepticism about the current technological maturity of AI assistants in spaceflight contexts.

Engineer 1: *"Everything we've tried so far worked very poorly. Technologically, some of the solutions that we've used were of the classical type, where you had to train the system to recognize your voice. And even then, the performance was not great, because the system itself was really limited in computational power... It was consistently terrible. [...] If you have a solution for operational use, it needs to work 100% of the time."*

This sentiment was echoed by another participant with engineering responsibilities for in-mission operations:

Engineer 2: *"In space operations, things have to work. Not six times out of ten, not seven times out of ten – but ten times out of ten. If it works, then sure, but it needs to work reliably and consistently every single time."*

Several participants emphasized that current AI assistants often fail to meet those standards, citing issues such as long response times, unexpected behaviors, and inaccurate outputs. These shortcomings were viewed as particularly problematic in safety-critical settings such as EVAs.

Instructor 1: *"The problem is, for the time being, if you're completely relying on such an artificial intelligence assistant, you still have some unexpected behaviours. [...] I'm not sure if I would put an AI assistant immediately in a [safety] critical environment, like an EVA or Moon exploration. I would rather put it in a support function, until it's really reliable in the response."*

Scientist 1 added that the narrow training scope of most IPAs makes them ill-suited for complex, dynamic environments, suggesting that human crew members are still more capable of holistic judgment.

There was also a strong preference for human communication over AI in situations where ground contact remains viable, such as on the ISS. Participants highlighted the value of interpersonal trust, shared context, and linguistic nuance, all of which are difficult to replicate in human-AI interaction.

Instructor 2: *"For an ISS EVA we have immediate direct communication. I'm sure the crew would always want to talk to their capcom, because they know them, they've trained together. [...] Why would you not talk to someone on the ground and go to the AI? There would just be no advantage, it would only introduce a risk of miscommunication."*

Taken together, these insights suggest that while IPAs may play a supportive role in routine or non-critical tasks, current limitations in their reliability and predictability preclude their use as a substitute for trusted human interaction, especially in mission-critical scenarios.

4.3 Offline Availability

The necessity for astronauts to operate independently from terrestrial mission control centers likewise emerged as a crucial requirement across interviews. Participants consistently emphasized that, in the absence of real-time communication, particularly during missions to the Moon's far side or Mars, intelligent personal assistants must be fully functional offline.

Instructor 3 pointed out that the relevance of an IPA depends strongly on the mission context: *"It largely depends on where your EVA is taking place. If it's on ISS, then maybe not. But if you're on Mars, you'd probably need something like this, because you won't have real-time communication with the mission control centre."*

Engineer 1 raised technical concerns about embedding IPA systems directly into EVA suits, especially the challenge of implementing reliable AI locally without relying on Earth-based servers: *"But how do you do that (integrating the AI assistant in the suit)? Because then you will need to implement the AI locally, it will need to be either in-suit, or it would have to be on a spacecraft. But ideally in suit, how do you implement something like that in suit?"*

Beyond connectivity, the issue of hardware viability also surfaced. Engineer 1 noted the limitations imposed by energy consumption and computational power, particularly for radiation-hardened environments. Similarly, Astronaut 2 emphasized the importance of local control for mission-critical data and functionality:

Astronaut 2: *"I want to have [local] control. I don't want to have to ask the mission control centre, for example, to toggle information in my visor. Because I might not even have a connection to the mission control centre. So all this data, all this functionality, I want to have with me."*

In scenarios such as lunar far-side EVAs or deep cave exploration on Mars, crew members may need to retrieve localized fault diagnosis procedures or verify oxygen reserve levels without ground input. Throughout the interviews, multiple participants pointed out that in such cases, a failure of the IPA could risk the life of the crew. The assistant must thus support autonomous access to important procedural and diagnostic content.

Together, these perspectives underscore that offline operation is not merely a convenience but a mission-critical necessity. They point toward a need for self-contained, resilient, and locally executable IPA systems that can support astronauts autonomously under constrained conditions, without relying on cloud-based processing or external control infrastructure.

4.4 Multimodality: Combining Audio and Visual Information

Most participants described voice interaction with an AI assistant as intuitive and hands-free, particularly well suited to the operational realities of space environments. **Scientist 4**, for example, drew inspiration from science fiction portrayals and explained: *"I would prefer to talk... I wouldn't like to have a lot of texts to read when you can just say it."*

However, several participants emphasized that relying solely on audio communication could be limiting, especially during tasks that require situational awareness or procedural clarity. The addition of visual information, either on displays or through AR, was described as important for maintaining efficiency and safety.

Astronaut 1 noted the risk of reducing information to the audio channel: *"I think that I would not give up augmented reality. You know, voice can be an option to switch features on or off. But it might not always be safe [for more complex tasks] because you completely lose situational awareness if you are just waiting for a voice to respond to you."*

Engineer 4 highlighted the benefit of visual content for quick reference: *"I'd rather be able to scan what it says."*

Engineer 3 emphasized the value of visual aids during procedural work: *"You need procedures displayed somewhere... to show you the next three steps."*

Astronaut 3 envisioned an IPA that could integrate voice commands with augmented reality elements to support lunar surface operations: *"Maybe you have Siri with you and you tell her to put up the map for today's spacewalk, or the road to the next point. Then I would say, 'Hey, can you put up in my head-up display a projection of the track?' And later, 'Okay, now it's in the way, I don't want to see it anymore. You can take it off.' Things like that."*

These perspectives suggest that while audio-based interaction may serve as the primary modality for AI assistants in space, it should be complemented by visual output. This is particularly important for navigation, spatial orientation, and procedural tasks. AR displays were widely seen as a promising solution for presenting such information in a non-intrusive and context-aware manner.

Together, these four themes reflect a shift in how IPAs must be conceptualized within human-systems integration for space: not as convenience tools or as full replacements for human tasks, but as flexible, reliable, multimodal, and offline-capable systems designed to actively support astronaut-centered autonomy and decision-making during missions.

5 Discussion

This study examined the requirements and limitations of IPAs for future human spaceflight missions beyond Low Earth Orbit. Based on insights from 15 domain experts, including 3 astronauts, we identified four key requirements: flexibility, reliability, offline availability, and multimodal feedback. These differ meaningfully from terrestrial IPA use cases and are grounded in specific operational contexts such as EVAs, anomaly response, life support monitoring, and navigation.

Table 2 Comparison of IPA systems across four key criteria derived from expert interviews: offline availability, flexibility, reliability, and multimodal feedback.

System	Offline Availability	Flexibility	Reliability	Multimodal Feedback
CORE	Offline with local LLM, RAG and KG	Dynamic adjustments via vector database, and knowledge graph	Designed for transparency and robustness	Combine audio and AR overlays
METIS	Offline with local LLM, RAG and KG	Dynamic adjustments via vector database, and knowledge graph	Designed for transparency and robustness	Text only
CIMON	Not offline, cloud dependence	Fixed interaction scripts	Tested in controlled ISS setting, limited robustness	Audio and screen-based interaction
Alexa (Artemis I)	Not offline, requires cloud connectivity	Rigid, rule-based structure	Demo only, not reliable for mission use	Audio only
AI4U	Some offline capacity with trained modules	Learns tasks during analog mission training	Early stage, no long-term reliability shown	Audio only

5.1 Flexibility in Dynamic Operations

Overall, the study participants expressed a strong preference for IPAs that are highly adaptable in managing tasks whilst catering to a wide range of user needs during future human spaceflight missions. In contrast to terrestrial settings, where assistants support routine activities, future missions will demand on-the-fly adjustments to task sequences, unexpected procedural deviations, and adaptive communication styles.

For example, during an EVA, an astronaut may need to reprioritize steps in a checklist or receive contextual guidance for an unforeseen problem. Current rule-based IPAs are limited in these situations. Therefore, the participants suggested that there is a need for assistants that can understand intent, dynamically restructure procedures, and shift between brief, directive responses and more detailed explanations based on situational or personal needs.

Similar requirements have already been elaborated in other domains. For instance, in an effort to enable Unmanned Aerial Vehicles to better handle unpredictable mission scenarios, Keneni et al. advocated replacing traditional rule-based AI with a hybrid approach that integrates neural networks and fuzzy logic into a single system [20].

In the context of flexibility, prior work on human-systems integration (HSI) has mostly emphasized dynamic function allocation and adaptive control between human and automated systems [15, 35]. These approaches often focus on high-level decisions about when to delegate tasks or shift roles based on cognitive workload or mission state, giving the system a specific degree of flexibility depending on the situation. While valuable, this system-level framing partly differs from the type of flexibility highlighted in our study. As there is a difference between adaptable automation, where the human explicitly controls how automation is applied, and adaptive automation, where the system itself changes its behavior in response to inferred user or task states [11].

In our study, the participants described a need for interaction-level flexibility, namely, IPAs that actively adapts within tasks and requests to user preferences, communication styles, and situational needs, not only to the level of astronaut autonomy. Rather than passively taking over tasks, the IPA must respond to astronaut intent, restructure procedures dynamically, and provide multimodal feedback in a way that enhances and extends, rather than replaces, astronaut autonomy and active decision making, which would represent a form of adaptable automation, enhanced by adaptive elements that respond to inferred intent or context.

This aligns with findings in prior HSI studies, showing that adaptable automation leads to better task performance and reduced workload [11]. Given the safety-critical nature of spaceflight, astronauts may prefer the perceived control offered by adaptable systems, aligning with their desire to direct IPA behavior in context-sensitive ways (e.g., choosing terse vs. verbose feedback, or manually initiating a procedure switch).

Design Guideline 1. *IPAs for spaceflight should primarily implement adaptable automation that allows astronauts to manually adjust task flow, modulate interaction style, and influence system behavior in real time. Rather than taking over all decision-making, the assistant should support astronauts by enabling control over task sequences (e.g., skipping, reordering steps) and tailoring feedback (e.g., short vs. detailed explanations, communication style). Rather than replacing astronaut autonomy, adaptable support should be complemented by selective elements of adaptive automation, such as context-sensitive suggestions, provided they remain transparent and user-overridable.*

From a technical standpoint, this could be achieved by integrating a GPT-based language model with a graph retrieval-based framework like GraphRAG [14] as well as steering vectors to for example adjust the language models tone based on the astronauts needs and preferences [22]. Such a system would allow the assistant to retrieve and adjust mission plans on the fly, adapt its interaction style to individual preferences, and support procedural changes without relying on real-time communication with Earth.

5.2 Reliability in Safety-Critical Contexts

Reliability was consistently suggested as one of the most important requirements for the use of IPAs in human spaceflight missions. Participants drew attention to past frustrations with unreliable assistants such as CIMON or Alexa, noting delays, misinterpretations, or incorrect outputs. In high-risk operational settings, such failures are not just inconvenient but potentially safety-critical. While users on Earth can fall back on human support when digital assistants fail, astronauts in deep space must rely solely on the system, making the error tolerance effectively zero. As such, participants emphasized that trust is a prerequisite for use. This aligns with prior research, which shows that trust in automation is closely tied to intended usage [12].

Participants also highlighted the importance of explainability, commonly defined as "the ability for the human user to understand the agent's logic" [37, p.678]. Our research suggests, that being able to understand where a recommendation is coming from, how confident the system is, and what reasoning underlies its output could help astronauts to calibrate their trust in the IPA. This, in turn, helps avoid overreliance, while also ensuring that astronauts are not dismissing correct recommendations due to a lack of confidence in the system. These findings are supported by previous work on human-agent teaming and trust calibration [2, 37], and align with NASA's ethical guidelines for AI use, which state that "Solutions must clearly state if, when, and how an AI system is involved, and AI logic and decisions must be explainable" [30, p.3].

Design Guideline 2. *In safety-critical space environments, trust and explainability are essential for effective human-agent collaboration. Astronauts must be able to understand and verify the assistant's responses, especially when no human fallback is available. IPAs should therefore provide clear explanations, indicate confidence levels, and make the origin of their recommendations understandable to support explainability and trust calibration.*
From a technical standpoint, this could be achieved by grounding IPA outputs in structured, verifiable knowledge sources, such as KGs and by integrating RAG architectures [14, 26]. These approaches connect the generative capabilities of LLM models with reliable content and support explainability by showing astronauts where the output is coming from.

5.3 Offline Availability for Autonomous Operations

Participants stressed that an IPA tailored for space missions would need to function offline, citing the need for local autonomy and reliability as key reasons. The connection between an AI system's accuracy and its perceived trustworthiness is well established [25], and is further amplified in safety-critical contexts [46]. During operations on the Moon's far side or on Mars, communication with Earth will be delayed or unavailable, resulting in a situation where IPAs will have to operate fully offline and deliver reliable functionality without any external humans support (e.g., from mission control centres).

Under such conditions, a system's trustworthiness will inevitably be even more dependent on its perceived reliability. IPAs that fail or degrade under communication constraints could not be relied upon in critical operations. As such, the IPA must be resilient, self-contained, and capable of delivering consistent performance regardless of external connectivity.

Design Guideline 3. *In environments where real-time communication with Earth is not possible, such as during Mars missions or lunar operations in shadowed regions, IPAs must function autonomously to support astronaut decision-making and task execution. This requires full offline operability, ensuring that core capabilities remain available even without external support.*
From a technical standpoint, this can be achieved by deploying optimized, hardware-efficient LLMs that utilize reasoning (e.g., Magistral [32]) and combine them with reasoning over knowledge graphs [7]. These approaches allow advanced IPA systems to run locally on wearable or embedded computing platforms, maintaining functionality in communication-constrained conditions.

5.4 Multimodal Feedback for Situational Awareness

The participants explained that relying only on audio information could reduce performance, for instance, when astronauts are hands-busy or have limited visual focus, additional output modes become critical. This observation aligns with Multiple Resource Theory [49], which suggests that human attentional capacity is limited and can be supported by distributing information across multiple sensory channels. Accordingly, multimodal interaction has been found to improve spatial orientation [10], safety [44], as well as learning performance of users [40]. AR technology integrated into the astronaut helmet could in this sense allow astronauts to quickly scan instructions, interpret navigation data, or check system diagnostics in a spatial, safe, and intuitive manner, reducing cognitive effort compared to relying on voice or text alone.

Participants described scenarios where audio feedback alone led to confusion or missed instructions. The combination of spoken dialogue with visual overlays could reduce cognitive load and could therefore support better situational awareness. Visually seeing the next three checklist items while hearing confirmations could also create redundancy and therefore reduce the chance of error.

Design Guideline 4. *IPAs should integrate with AR systems to provide layered, context-aware information that shows spatial cues, diagnostics, or mission timelines. These should be linked to the underlying knowledge base, allowing astronauts to explore connections or clarify specific items visually. We would furthermore recommend a combination of different modalities, such as voice and sounds, written text, and visual AR output, to enhance the intuitive understanding of data, to reduce cognitive load, and to create redundancy, especially in safety-critical scenarios. Yet, a critical balance should be achieved to only provide the astronaut with necessary and supportive cues to ensure situational awareness and to balance workload.*

5.5 Tensions and Trade-offs: Balancing All Four Themes

Our findings, however, do not only show four identified requirements (flexibility, reliability, offline availability, and multimodal information) that should all be fulfilled for space-related IPAs, but also a tension between each of them. Fulfilling one could introduce additional friction for another requirement, requiring a balance between the identified factors.

For instance, participants expressed a strong preference for assistants that can dynamically respond to changing mission conditions or user needs (flexibility). Yet, making the assistant more flexible in its responses could create a higher risk of wrong or unexpected answers affecting its reliability.

Similarly, offline availability was framed as a non-negotiable requirement for missions beyond Low Earth Orbit. However, the need to operate without access to cloud-based resources raises questions about how to support and enhance explainability when the assistant cannot access external databases or justification mechanisms to allow for a high degree of flexibility.

We likewise came across instances of ambivalence surrounding the assistant's interaction style. While the idea of a conversational agent that adapts emotionally to user stress or mood was welcomed in theory, many participants voiced discomfort with systems that attempt to mimic human behavior too closely. This was especially the case in situations involving risk or time pressure, where predictability and control took precedence over social or affective engagement.

Moreover, the integration of visual and auditory modalities was seen as critical to support astronaut performance in cognitively demanding environments. Yet this combination also introduces the risk of sensory overload if not carefully calibrated to task demands. The challenge lies not only in offering multiple channels of information but in ensuring that these are presented in ways that enhance rather than compete for user attention, while ensuring reliability of the system that in an ideal scenario could also react to as many novel situations as possible based on its database while also being available offline.

Therefore, all themes can be seen as important factors that should be in balance with each other to balance competing goals. A one-size-fits-all approach is unlikely to succeed. Instead, systems must be context-aware, adapting their behavior to the astronaut's current needs and situation, workload, and environment while individually adjusting the specific requirement based on its importance in the given situation or mission.

5.6 Toward Human-Centered IPA Design for Spaceflight

To summarize, our findings indicate that future IPAs designed for space exploration must explicitly address the requirements of flexibility, reliability, offline availability, and multimodal interaction. The presented insights from astronauts and domain experts emphasize these important design criteria, exceeding the capabilities of traditional rule-based systems and narrow AI. Only the presented approaches (see related work) shown by METIS [6] and CORE [5], integrating KGs [7], generative AI (GPT models) [32], RAG [26], and, for instance AR, could be technical approaches to fulfill the requirements identified in our study (shown in Figure 2). Overall, our study reaffirms the importance of a human-centered approach to space technology development, what we define as a balanced astronaut-oriented design [4]. This approach prioritizes the astronaut's perspective first, while iteratively involving all relevant stakeholders in a co-design process. Rather than retrofitting existing AI systems for extreme environments, IPAs should be co-designed with the end-user in mind, focusing not only on technical feasibility but on the real operational needs, constraints, and preferences of astronauts. Following this approach could also help with balancing trade-offs between the different requirement themes that emerged during the study, for example, because it enables iterative feedback from astronauts during the design process, developers can tailor the assistant's interaction style (flexibility) to different task contexts without compromising trust (reliability), even in offline conditions where fallback options are limited.

6 Conclusion and Future Work

Our work underscores the importance of IPA technologies for future space missions, particularly those beyond low Earth orbit, where crews will face complex tasks, high uncertainty, and limited access to ground control. Through semi-structured interviews with astronauts and space experts, we identified key design challenges for conversational agents in this environment and proposed solutions grounded in recent advancements in natural language processing.

Our proposed technical approach centers on a flexible IPA capable of adapting to different tasks and interaction styles, supported by GPT models. Unlike narrow AI systems, these models offer advantages in reasoning, creativity, and handling unforeseen scenarios. Equally important is system reliability, which directly shapes user trust and engagement. To address this, we recommend integrating RAG and knowledge graph technologies, enabling transparent, verifiable outputs during critical operations, such as shown with METIS [6] and CORE [5].

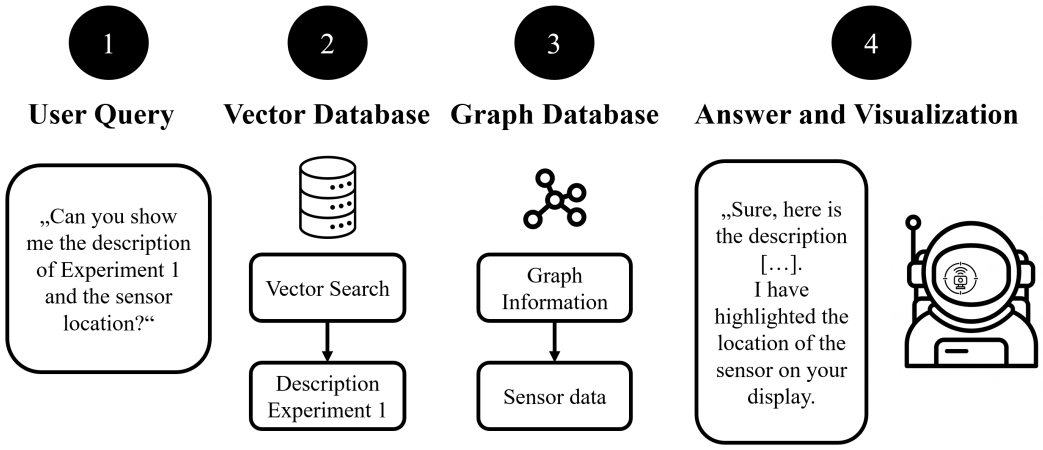

Figure 2 Example integration of GPT, RAG, KGs and AR.

Table 3 Design considerations for intelligent personal assistants in spaceflight, organized by core user needs, mission-specific constraints, and actionable recommendations.

Theme	Representative Use Cases	Spaceflight-Specific Challenges	Design Recommendations
Flexibility	EVA procedures, anomaly handling, dynamic checklists	Requires real-time adaptation without ground control input	Support task reprioritization, interaction personalization, and flexible procedure handling through adaptable and selectively adaptive automation
Reliability	Life support queries, system diagnostics, checklist execution	Failures may impact safety; no fallback to human assistance in critical moments	Ensure consistent, explainable outputs grounded in trusted data; integrate confidence levels and traceable reasoning to aid trust calibration
Offline Availability	Lunar far-side EVAs, Mars surface operations, habitat troubleshooting	Communication blackouts and latency limit support from mission control	IPAs must operate autonomously with locally embedded knowledge, optimized models, and robust decision-making capabilities
Multimodal Feedback	Navigation, maintenance workflows, procedural training	Audio-only feedback limits situational awareness during hands-busy tasks	Combine voice with visual cues (e.g., AR overlays, helmet HUDs) to support spatial understanding, reduce cognitive load, and enhance safety

Offline availability is another essential requirement. Given the communication constraints of lunar and Martian missions, IPA systems must operate autonomously and efficiently without cloud connectivity. Advances in compact, hardware-efficient language models support the feasibility of such offline systems. Finally, to support situational awareness, we propose combining voice-based interaction with visual information presented through AR, allowing astronauts to interpret complex content such as checklists, navigation instructions, or system diagnostics more intuitively.

Looking ahead, our future work focuses on evaluating and refining the CORE system through applied experimentation and user studies. Specifically, we aim to explore the following directions:

- We will integrate the system into a high-fidelity simulation of an Artemis mission. Domain experts will perform EVA scenarios within a virtual reality environment modeled on the Moon's south pole, augmented with AR overlays for navigation and procedural support. We will assess performance across different task contexts and system variants, such as KG plus RAG versus GPT only, or with versus without confidence scores.
- We will investigate optimal strategies for distributing content across visual and auditory channels. This includes identifying which types of information, such as procedures, alerts, or spatial data, are most effectively conveyed through voice or visual displays to minimize cognitive load.
- We will evaluate the robustness of the speech recognition component in acoustically challenging conditions and across diverse speaker profiles. This includes testing and potentially integrating models such as Whisper [36], with a focus on accuracy and responsiveness during simulated EVA activities.
- We will extend the system with computer vision capabilities to support real-time monitoring of both the environment and astronaut activity. This includes hazard detection and geological analysis. Detected features will be visualized through AR overlays to assist decision making in operational settings [39, 16, 3, 47, 29, 41].

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Multi-Axis, Multi-Material Additive Fabrication of Multi-Layer Conformal SMD Circuitry to Support In-Space Mission Resilience

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Abstract

This work presents the development and evaluation of multi-material, multi-axis Material Extrusion (MEX) additive manufacturing combined with electroplating for the fabrication of complex conformal circuitry. The proposed approach enables the direct printing of functional electronics onto conformal surfaces, while offering a lower-cost and lower-complexity alternative to conventional PCB manufacturing and other in-space electronics fabrication methods. A key contribution of this work is the introduction of small multi-material bridges as a lightweight and scalable solution to miniaturisation challenges in 3D-printed electronics. The printed circuits' physical dimensions were analysed and compared among samples, and their electrical performance was benchmarked against traditional FR4 PCBs. Lastly, the role of such a system is evaluated in the context of a space exploration mission. While the printed circuits exhibited increased noise and reduced reliability, they successfully demonstrated the ability to regulate and deliver current. The results highlight the potential of MEX-based additive manufacturing as a potential lower-cost alternative technique to proposed in-space additive electronics manufacturing processes.

2012 ACM Subject Classification Hardware → Flexible and printable circuits; Hardware → Full-custom circuits

Keywords and phrases Space Digital Fabrication, Additive Manufactured Electronics Systems, 3D printed electronics, In-space manufacturing

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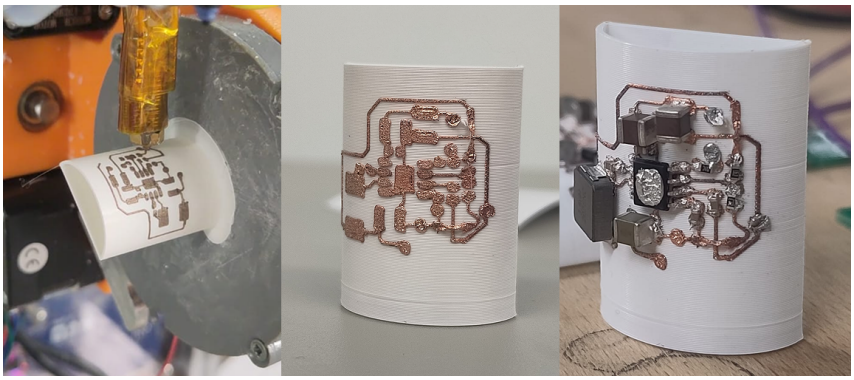

Figure 1 Example circuit a) while printing b) once electroplated and c) fully assembled.

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1 Introduction

The benefits of Additive Manufcaturing (AM) are particularly important for the low-volume, high-variety nature of the space industry. AM allows for the creation of intricate, lightweight structures that better utilise a given volume while at the same time minimising waste. Currently, there already exist many companies utilising AM on Earth to print components for space, great examples include Relativity Space printing entire rockets [5] or SWISSTo12 printing complex antenna arrays for communication satellites [14].

But the potential of AM is not bounded to Earth, in fact, the benefits of AM become more relevant and noticeable when used in a space-based ecosystem. Effective resource utilisation and waste minimisation is crucial for sustainable space missions and settlements. Additionally, AM processes are almost always digital in nature, enabling for different designs to be fabricated from a given machine, allowing for in-mission upgrades and increasing mission flexibility. In recent years, different AM techniques have been demonstrated in microgravity, including Material Extrusion (MEX) [1], Digital Light Processing (DLP) [2] and Directed Energy Deposition (DED) [12]. From these demonstrators it can be seen that even within a microgravity environment some additive techniques work and while the printed parts exhibit some differences, the remain structurally sound [8]. The main focus has been on printing structural elements in order to enable the construction of large space structures [7], produce replacement parts for satellites [9] or improve tools for astronauts [16]. These are exciting applications that will decrease Earth dependency and open up a whole dimension of possibilities when it comes to space activities. However, our modern systems are not purely mechanical, almost everything contains electronics in one way or another. Space technology is not an exception, and every subsystem heavy relies on them, from life support to propulsion, all the way to telecommunications. If our space missions ever want to eliminate Earth dependency, they will need to be able to locally fabricate their own electronics.

With the benefits of AM for space in mind and understanding the need for space electronics fabrication, a few academic and commercial initiatives have emerged to attempt to bridge this gap. Among these you can find Space foundry who demonstrated the use of Plasma Jet Printing to produce circuitry in a parabolic flight [3], Nscrypt published regarding the fabrication of circuits using silver inks for space [10] and HummInk which are working on an ESA project to upgrade their ink-based printer for in-space operation [13]. Apart from these, there are some other actors involved in additive electronics fabrication but their interest to pursue space fabrication is less clear. Overall, there appear to be two main method families, the plasma-based methods and ink-deposition methods. Both of these have their respective advantages and disadvantages. For example, ink methods have been shown to be able to achieve accuracy < 100 nm [15] but controlling the dynamics of the ink droplets in microgravity adds complexity [6]. On the other hand, plasma methods do not require solvents or curing making them more efficient in terms of launched mass per fabricated part but the plasma containment and longevity of the nozzles reduces the potential practicality and sustainable use of these methods. Both of these families of methods have been shown to work within multi-material printing ecosystems, first printing substrates and then conductive traces, even on conformal substrates. In this work, we propose the use of multi-axis, multi-material MEX with electroplating for the in-space fabrication of conformal circuitry as a lower cost, less complex and potentially more robust alternative.

In this work, it has been shown how to use low-cost multi-axis, multi-material MEX in order to produce conformal SMD, multi-layer 3D-printed circuitry. The design, printing and post-processing of such circuits have been thoroughly covered while providing key process

insights. The circuits have been fabricated, assembled, electrically, thermally tested and compared against regular FR4 PCB counterparts. Finally, the system was evaluated and it has been discussed how it fits within a human-space environment.

2 Methodology - Sample design and fabrication

2.1 Circuit Design

The chosen circuit was a DC-DC switching voltage regulator circuit based on the TPS54627DDAR IC from Texas Instruments. The purpose of the circuit was to actuate a nichrome wire based burn wire system within a hypothetical deployment system (e.g rocket or satellite) where the available input voltage is 12V and a 0.9 Ohm nichrome wire is used. The circuit was designed using the WEBENCH tool from Texas Instruments with a regulator target voltage of 1.3V (0.4 V on Schottky diode + 0.9 V on burn wire) in order to dissipate 1 W through the burn wire as stated on [11]. The circuit schematic can be seen on Figure 2.

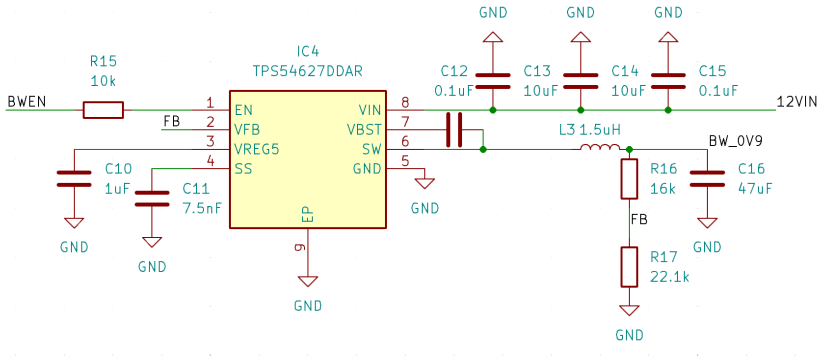

Figure 2 Proposed Burn Wire circuit based on TPS54627DDAR.

The circuit was laid out on KiCad following closely the data sheet of the TPS54627DDAR IC. The layout was made compact to make it comparable to real-life PCB circuit layouts, while keeping in mind the capabilities, tolerances and resolution of printer. To demonstrate the fine features achievable on this work, the design was done purely with pads and 0.25mm traces, even though for thermal and signal integrity issues it is often recommended to use larger polygons and ground pours. The passive components were selected to be 0603 or larger as with the current set up, printing 0402 pads resulted unreliable. Due to the complexity of the regulator design, the circuit was not achievable within 1 layer routing which required to use vias as there were 2 pairs of intersecting traces. For the inputs and outputs of the circuit, instead of using connectors, a variety of circular pads were exposed for the 12VIN, GND, BW-0V9, BWEN nets. The idea behind this was to then be able to connect wires to these terminals and interface the circuit. The resulting layout can be seen in Figure 3. In order to have a benchmark of the printed circuit, the circuit was sent to manufacture at a regular PCB manufacturer as a 2 layer FR4 board without any modifications.

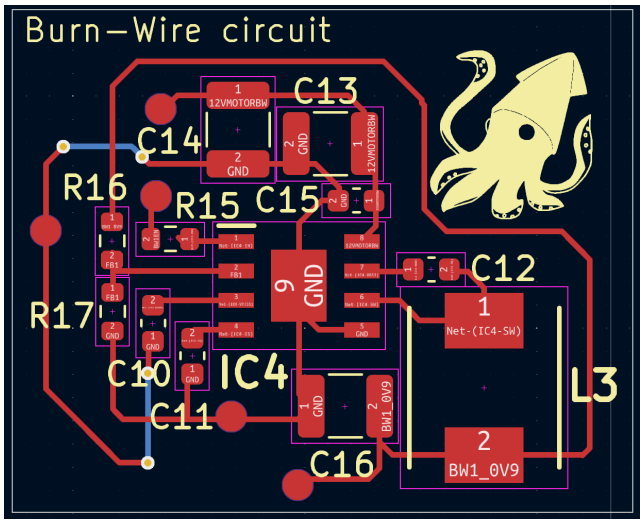

Figure 3 Proposed Burn Wire circuit layout.

2.2 3D Modelling and Tool-path generation

The following sub-section describes in detail how the circuit was modeled and how the tool-path for the conformal traces was designed and carried out. The printer used to print these samples is an E3D toolchanger with an Open5X modification, therefore software-wise the Open5X Grasshopper-based G-code generator was used [4]. Additionally all the modelling of the substrate, generation of the traces and pads was done in Rhino and Grasshopper. In this instance, the circuit was drawn manually in Rhino using a 1:1 print from the KiCad layout. Once the circuit was drawn planarly it would be projected onto the target substrate and offset from the substrate by the printing layer height (0.1mm).

2.2.1 Substrate

The target surface was a single curvature, spline-based extrusion. Such a surface could resemble the curvature of the fuselage of a rocket, the wing of an extraterrestrial UAV or the linkage of a rover's robotic arm. The substrate was printed out of PLA printed at 235 °C due to the long nozzle configuration for multi-axis printing at 40 mm/s. The substrate was reinforced with a back plate to prevent deformation due to thermal warping while printing the substrate itself and while printing the traces on it. The substrate was sliced using Prusaslicer, with a layer height of 0.2mm and printed with a 0.4mm nozzle. The substrate and its dimensions can be seen in Figure 4.

2.2.2 Traces and pads

The traces and pads were printed out of Electrifi filament at 145 °C, 5 mm/s using a 0.25mm nozzle. All of the electrifi based printed was done in two sequential conformal 0.1mm layers of the entire circuit. The traces joining the different pads consisted of individual polylines of different lengths and orientations. All the pads were designed as scaled down (by 0.25mm) rectangles with a 100% rectilinear infill pattern and outer perimeter. The direction of the rectilinear infill was made the same as the z-axis layer height direction of the substrate. It was found that the adhesion of the Electrifi traces was greatly improved by printing along the layer heights of the substrate instead of perpendicular to it. It was also found that to

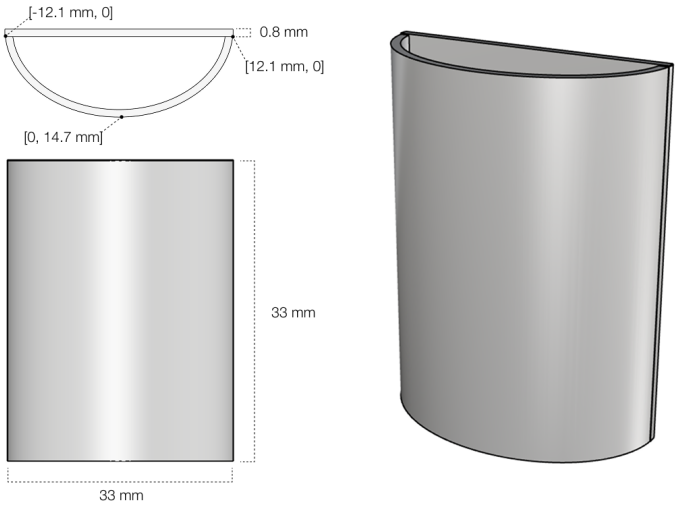

Figure 4 Physical dimensions of circuit conformal substrate.

minimise the effects of retraction and trace detachment from travel motion, it was best to first print all the traces and then print the pads than vice-versa. Additionally, when printing the pads it was found best to first print the infill and finish by doing the outer perimeter, this helped the pads maintain a rectangular shape and better adhere to the substrate. All the traces and pads can be seen in Figure 5, each of these were one continuous print.

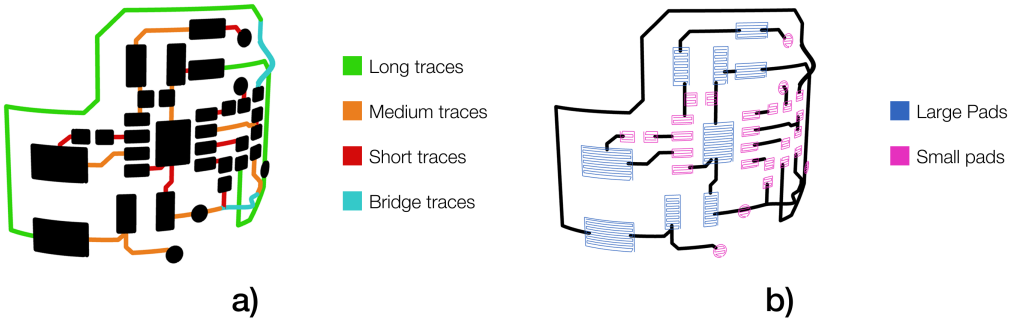

Figure 5 Projected traces and pads overview.

2.2.3 Bridges

The circuit counts with two bridges: one on the FB net and on the GND net (Figure 3). These bridges are made out of single trace of PLA, printed at 235 °C, 1 mm/s using the 0.4mm nozzle. The bridge and the bridging trace are splines, procedurally produced in a grasshopper script. The script takes into account the location of the intersection, the substrate surface (in order to make the bridge normal to the surface) and some user-defined parameters like height and width of the bridge. In these samples the bridges were 1.15 mm tall from the substrate and 2.6 mm wide, these values were found to work consistently but the authors believe they can be made smaller. An important consideration with these bridges is that they should leave empty space on top of the bridged trace, in order to allow access to the electrolyte when plating. Lastly, another important consideration when attempting

to produce these bridges and their respective traces is that the XY nozzle position of the tool-heads needs to match to 0.1 mm (around half of the printed trace), otherwise the bridging trace might miss the bridge and droop, potentially shorting with the bridged trace. Figure 6 shows the differences between the intended and the actual printed bridge structures in this work, with a microscope image of one of them.

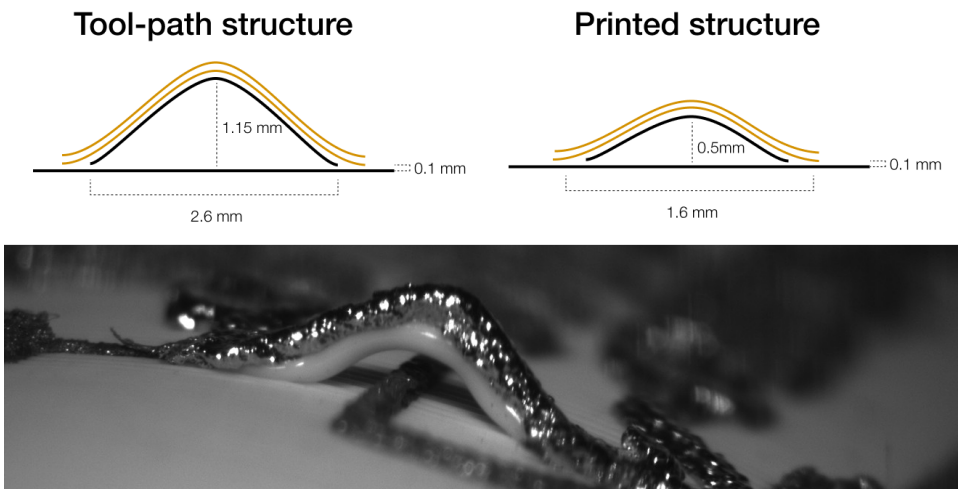

Figure 6 Example comparison between the theoretical and the printed bridge structure with a microscope image from one of the bridges.

2.3 Electroplating

In order to enhance the conductivity of the deposited Electrifi traces and make them comparable with traditional PCBs, the samples were electroplated. The electrolyte consisted on a copper sulphate solution with sulphuric acid and brightener additives. The solution was poured in a shallow round beaker and the copper anode submerged and held up by a clamp. The cathode or part to plate required a more intricate setup as each individual trace/net required its own contact point with the power supply. The general setup is shown in Figure 7.

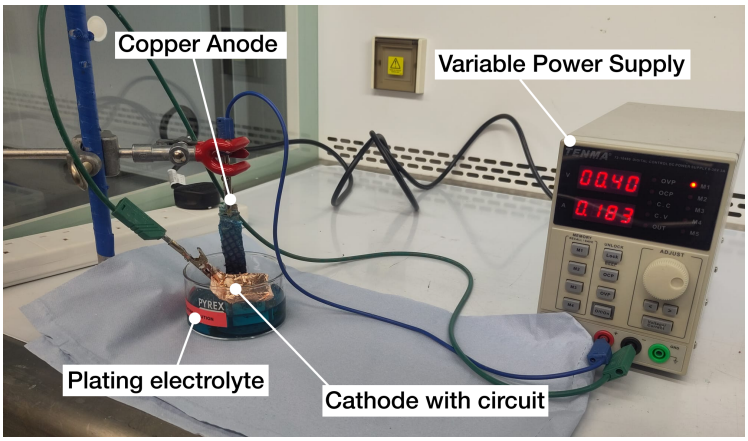

Figure 7 Electroplating setup overview.

The cathode setup was a small 3D printed rig with a base and a table-like structure, Figure 8. The plating samples would be placed on the base and under the table structure. The top of the table structure would be covered with 3-5 layers of copper tape. Using needles, the copper tape would be pierced and each needle would then touch a trace to plate. Lastly, the copper tape would be connected to the ground of the power supply to complete the circuit. The copper tape acts as support for the needles ensuring they maintain contact with the traces while also providing the electrical connection required for the plating to happen.

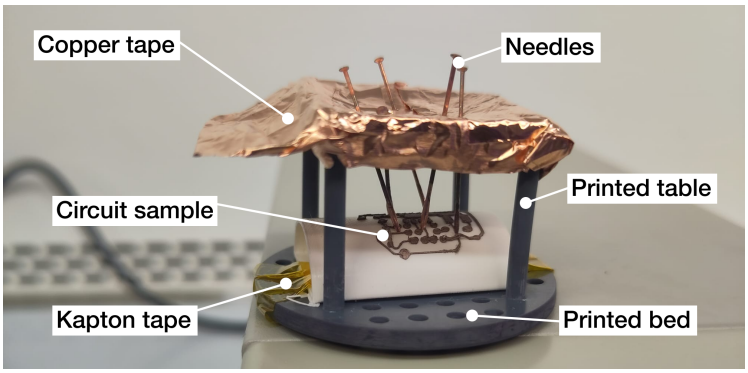

Figure 8 Detailed overview of cathode setup to enable precise plating control of different traces.

The plating was carried out at 0.4 V which depending on the amount of target traces to plate would yield currents from 5 to 20 mA for about 20 minutes. Due to the size of the needles and the compactness of the circuit, only about 5 needles could be mounted consistently at a time, requiring multiple plating cycles per sample until all traces were plated. To achieve the most uniform plating, similar-size traces would be plated together in the same plating cycles. After plating, the samples were all tested for potential short circuits between neighbouring pads/traces, before proceeding to the component assembly.

2.4 Component assembly

In order to place components on the 3D printed circuits, soldering is not an ideal approach (although possible once plated). Even the melting point of leaded solder is high enough to liquefy PLA and Electrifi, which results in deforming the structure of the printed pads. Instead, conductive silver epoxy resin was used (MP011123). The 0603 passive components required very careful placement of the component and the resin. This silver-based resin tends to self-adhere a lot, become flaky and not stick to other surfaces. These effects make it difficult to work with, especially at such small scales. The craftsmanship required to mount the components manually is certainly comparable with SMD soldering. However, with the epoxy's working time of 20 minutes the process becomes increasingly more difficult as time goes by and the permanent nature of such thermosets makes removing components or fixing shorts a more difficult task.

The approach taken in this work to mount the components was the following: Prepare the whole setup beforehand due to the strict 20 minutes working time. Prepare beforehand all the components planned to be mounted in this cycle and work under a microscope. Then in a small container mix a very small amount of epoxy (<0.1 g) using a larger spatula and set a 15 minute timer. Using a very small fine tip (e.g. the tip of a disposable syringe) pick up very small amounts of resin and deposit them in both pads, ensuring that there are no shorts (between pads and other traces) and that there will be enough resin for the component to

set into. Using plastic tweezers, pick up the component and carefully press it into the resin on the pads, the component (given there is enough resin) should remain in place. Repeat this process for each component until the time is up, trying carefully not to hit by mistake any other component as the resin is still fresh. Once cured, another pass of resin is given to the components to strengthen the bonding.

There was a small caveat to the mounting of the components on the printed samples. When projecting the circuit into the substrate, it had been mirrored along the axis of the substrate which went unnoticed until the mounting of the components. This mirroring effect resulted in a physically unfeasible layout for mounting the regulator IC. However, if the IC is to be flipped and mounted upside down, the pinout does match. Due to component lead times, instead of redesigning the circuit samples, the regulator ICs were mounted upside down. The pins were carefully epoxied to the pads and the ground thermal pad was grounded using epoxy to pin 5.

2.5 Testing methodology

In order to validate the circuits, three different tests were carried out. The tests included a physical dimension test, to understand the variation between the design and the 3D printed samples, an electrical test to compare the circuit performance between the FR4, 3D printed samples and the intended design. Lastly a thermal test was carried out to test whether exposures to very low temperatures (-80 C) would impact or damage the 3D printed samples.

The first test was a visual inspection using a microscope followed by 14 physical measurements. The microscope images were used to compare the width of 7 pads and 7 gaps between pads/traces on the three 3D printed samples. These measurements were randomly chosen around the high-density area of the circuit, shown in Figure 9. Additionally, the bridges were perpendicularly imaged, measured and compared among the 3D printed samples. The measurements were performed on the 3D printed samples after electroplating and without components.

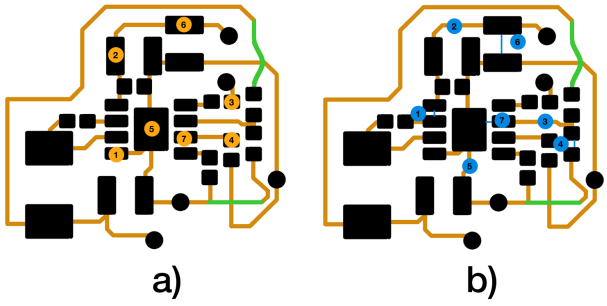

Figure 9 a) 7 pad width measurements b) 7 trace width and spacing measurements.

The second test performed was an electrical test where the circuits were connected to a 12 V power supply and the output voltage of the circuit measured using an oscilloscope (unloaded measurement). Due to issues with the regulator ICs, this test was only possible to be performed on one FR4 PCB sample (F2) and one 3D printed sample (P4). The circuits were then loaded with different load sizes (3.3 - 1.8 Ohm) and the output voltage and current were again recorded. The test results were compared among the two samples under the different loading conditions.

The last test was a thermal test where the F2 and C4 samples were placed in a freezer at -80 degrees for 1 hour and for 4 hours. After each cycle, they were taken out, left to reach room temperature, dried from condensed moisture and connected to the 12 V power supply. The voltages under unloaded conditions were measured and compared.

3 Results

3.1 Physical dimensions

The following section presents the measurements taken from the microscope imagery of the 3D printed samples. Figure 10 is an example, showing P3 from the top with reference scale.



Figure 10 Top view microscope Image of P3 after electroplating with reference scale.

3.1.1 Traces and pads

Table 1 shows the measurements described on Figure 9 a) for each of the three 3D printed samples. The majority of the pads in the samples display larger pad widths than initially designed for. The difference in values ranges from -0.03mm (P4, 5) to + 0.44mm (P4, 4). Sample P1 is the most dimensionally accurate sample overall with an 11% average error over the 7 different measurements. P3 and P4 are slightly less accurate at 16.8% and 16.3% respectively. The smaller pads, suffered the largest amount of relative error which was expected given the their overall dimensions is closer to the nozzle diameter and machine tolerances.

Table 2 shows the measurements for the 7 trace width and spacing measurements, described on Figure 9 b) for each of the 3D printed samples. The measurements taken on the trace widths (2,3 and 5) were mostly larger than intended across all samples, with relative errors ranging from -0.02 mm (P1, 5) to +0.10 mm (P3, 2). This was particularly noticeable on measurements 2 and 3, whereas in measurement 5, all samples followed the intended 0.25 mm more closely. Contrary to the pad and trace widths, the spacings were smaller than in the digital design, with relative differences ranging from -0.23 mm (P4, 4) to -0.06 mm

Table 1 Pad width physical measurements table.

Pad width measurement	Design (mm)	P1 (mm)	P3 (mm)	P4 (mm)
1	1.75	1.84	2.00	1.99
2	1.37	1.63	1.53	1.55
3	1.21	1.44	1.48	1.56
4	1.21	1.38	1.64	1.65
5	2.64	2.70	2.65	2.61
6	2.96	3.19	3.29	3.23
7	1.77	1.95	2.16	1.98
Average error (%)	NA	11.3	16.8	16.3

(P1, 6). As with the pad width measurements, P1 has the lowest overall average error (18.3%) across the trace width and spacing measurements resulting in the highest dimensionally accurate sample. On the other hand and similar to the other measurements, P3 and P4 are closer together at 23.6% and 21.3%.

Table 2 Trace width and spacing physical measurements table.

Pad width measurement	Design (mm)	P1 (mm)	P3 (mm)	P4 (mm)
1	0.34	0.26	0.17	0.22
2	0.25	0.30	0.35	0.27
3	0.25	0.30	0.28	0.31
4	0.59	0.43	0.42	0.36
5	0.25	0.23	0,27	0.26
6	1.55	1.49	1.38	1.38
7	0.48	0.34	0.40	0.34
Average error (%)	NA	18.3	23.6	21.3

3.1.2 Bridges

Table 3 displays the measurements taken from both bridges on all three 3D printed samples. The bridges are labelled as B1 and B2, when looking at Figure 9, the green traces mark the two bridges. B1 is the bottom bridge and B2 is the top bridge. The results show large disparities (in the range 26%-73% absolute errors) between the intended dimensions of the bridges and the actual printed ones. The width of the bridges had an overall better dimensional accuracy with values ranging between 26% (P4,B2) to 42.9% (P4,B1). Regarding the height of the bridges, the errors were significantly higher with values between 56.8% (P1,B1) all the way to 73.9% (P3,B1). On average, among the three samples there were no significant differences between B1 and B2. In terms of dimensional accuracy the best bridge was B2 on P1 and the worst one was B1 on P3, showing the same pattern as with the printed traces, where P1 has the highest dimensional accuracy and P3 the lowest. Both B2 P1 and B1 P3 are shown on Figure 11.

However, the dimensional accuracy of the PLA bridges is not the best metric to assess the quality of actual bridging, as it does not provide any information on the deposited Electrifi traces. Performing a purely qualitative assessment on the bridging traces, the best and worst bridges result to be B1 P1 and B1 P4, pictures in Figure 12. It can be seen how on B1 P1, the two Electrifi layers follow closely the PLA bridge and do not overflow or fall. On

Table 3 Bridge height and width physical measurements table.

Bridge name	Design	B1 P1	B2 P1	B1 P3	B2 P3	B1 P4	B2 P4
Width (mm)	2.6	1.60	1.89	1.58	1.73	1.48	1.92
Height (mm)	1.15	0.50	0.44	0.30	0.33	0.40	0.36
Width error (%)	NA	38.4	27.4	39.2	33.6	42.9	26.12
Height error (%)	NA	56.8	61.8	73.9	70.9	65.2	68.53

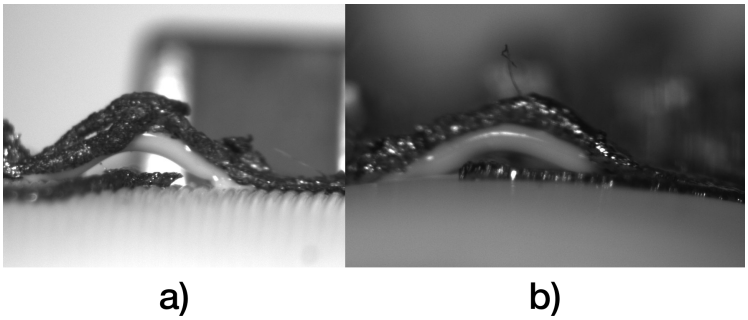

Figure 11 a) B2 P1, highest dimensionally accurate bridge, b) B1 P3, lowest dimensionally accurate bridge (Not to scale).

the other hand, B1 P4 appears to have a successful first layer but the second one appears to overflow and fall over the bridge. The falling of that trace actually touches the trace underneath causing a short. However, this is not an actual electrical issue as both of these nets are ground, they were just separated as part of the manufacturers layout guidelines to minimise noise from getting on the regulator's feedback signal.

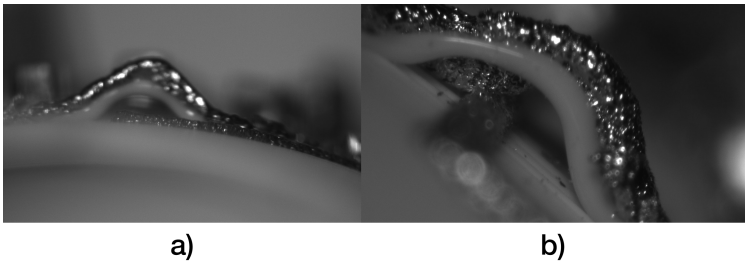

Figure 12 a) B1 P1 best deposited electrifi traces b) Close up of B1 P4, worst deposited electrifi traces (Not to scale).

3.2 Circuit testing

The results of the electrical testing carried out to F2 and P4 are graphically displayed on Figure 13. F2 showed a more stable behaviour overall. When unloaded the output average voltage was 1.3 V, as originally designed. When loaded with 1.8 Ohms, the average voltage dropped to a minimum of 1.20 V. The overall trend with F2 was a small decrease in voltage as a function of the loading which varied between (1.2 V to 1.3 V). F2 showed periodic high and low voltage peaks at a frequency of around 600 kHz, which reached over 1.5 V and below 1 V. P4 showed overall a less stable and in some cases, noisier behaviour as a function of loading. Unloaded, P4 output an average voltage of 1.42 V, +0.12 V higher than the original design. As it was further loaded the voltage lowered to 1.17 V under 2.7 Ohms.

Up to this point, the output voltage was stable with small traces of the 600 kHz periodic peaks and troughs. When loaded with 2.2 Ohm, the output voltage became significantly more oscillatory and with greater peak-to-peak voltage, following a sawtooth pattern at a frequency of around 1 MHz. However, the average output voltage did not drop significantly, remaining at around 1.15 V. Pushing the loading further to 1.8 Ohm caused a great drop in voltage down to about 0.25 V, the power consumption also dropped significantly to about 0.1 W and the sawtooth oscillatory pattern on the output voltage appeared at a frequency of approximately 600 kHz. Under the tests performed, both circuits were able to deliver similar amounts of power to the load, although F2 was able to do so more reliably, it did not show signs of failure and would likely be able to deliver larger currents.

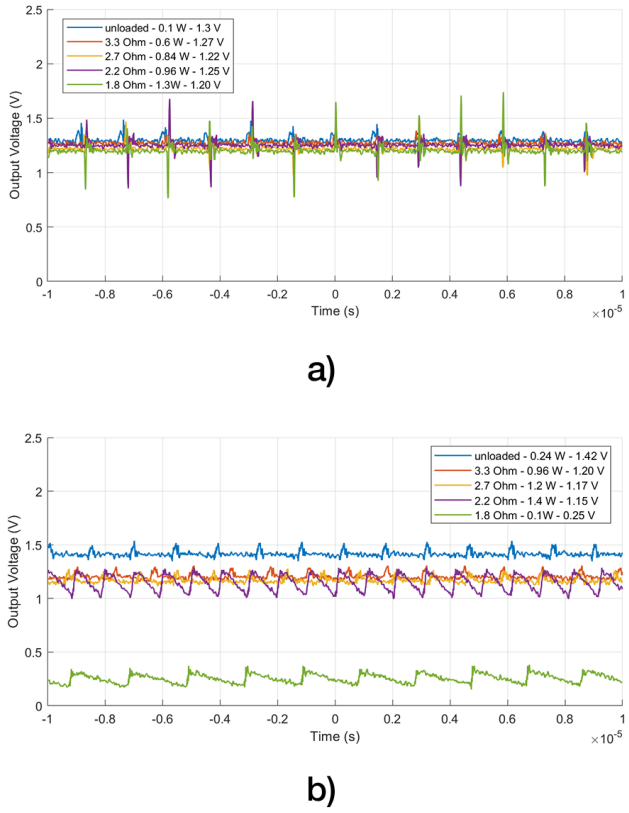

Figure 13 a) Output voltage of F2 under different loading conditions (10us) b) Output voltage of P4 under different loading conditions (10us).

3.3 Thermal testing

Figure 14 shows the output voltage after the low-temperature exposure to both F2 and P4 (unloaded). After both the 1 and 4 hour cycles, F2 does not appear to have suffered any effects as the output voltage before and after the testing look very similar. P4 shows higher disparities compared to before the thermal testing. The largest differences appear when comparing before and after the first 1 hour cycle, showing the sawtooth, oscillatory behaviour which appeared on the loading tests after certain loading. Between the 1 hour and 4 hour cycle it does not appear to have varied significantly with both tests resulting in similar output sawtooth patterns.

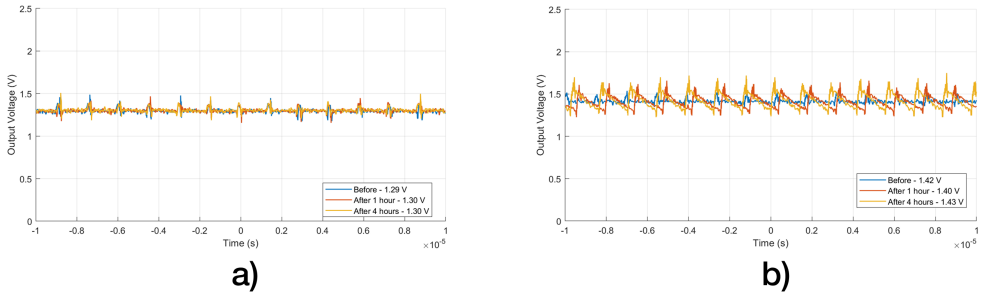

Figure 14 a) Unloaded voltage output for F2 throughout thermal testing b) Unloaded voltage output of P4 throughout thermal testing.

4 Discussion

4.1 Circuit fabrication evaluation

The results of the physical measurements showed that the printed Electrifi, almost always resulted on larger printed parts with errors in the order of 18%. Although significant, for this particular circuit layout, it was acceptable, demonstrating the ability to print dense SMD circuits with small footprints. The printed samples did not show shorting, apart from the B1 bridge on P4. The source of these dimensional differences is believed to be a combination of two factors. The first one, thought to be the main contributor to the size differences on the pads, is the retraction motion between travels. After printing a pad or a trace the nozzle will stop for 200 ms, retract and then move vertically, perpendicularly from the substrate. Often if there is Electrifi residue on the nozzle, some plastic will get adhered to the printed pad causing bulging in one of the corners (this effect can be seen repeatedly on Figure 10). This effect also makes the pads look more irregular and not resemble the rectangles/squares they were designed to be. The other effect causing disparities in both traces, pads and spacings has to do with potential errors and mismatches during the 5-axis calibration process. An error between the predicted and the actual centre of rotation (for either of the axes) will result in the substrate being on a different position to the intended g-code generator position. This error in position can appear on either of the 3 directions (X,Y,Z) and often results in differences in height when printing, hence differences on the thickness of the printed traces.

All the printed bridges were significantly different from the programmed toolpaths. This was thought to possibly happen, and the bridges were made larger intentionally. These disparities were caused by a combination of gravity, non-effective cooling and fast printing speed. In microgravity, the same settings used in this work would likely result on better dimensionally accurate bridges. On Earth, printing to achieve these free hanging structures requires either a faster cooling implementation or a printing speed reduction. When testing the manufacturability of the bridges it was noted that often it is more desirable to have a less steep bridge. If the adhesion between the Electrifi trace and the bridge is not sufficient, the printed trace will peel off when going through the steepest part of the bridge. Overall, the manufacturability, electroplating and functionality of the bridges were successfully demonstrated. One possible improvement for these structures could look at printing an adjacent PLA trace to prevent the Electrifi traces from dropping to make the circuit more resilient to small position errors between tool-heads.

Regarding the circuit performance, the F2 FR4 PCB sample served as a great benchmark to ensure that the schematic design and layout were sound and worked as intended. The periodic peaks seen on both samples are most definitely product of the switching action, as

the switching frequency of the device is 650 kHz. The amplitude and duration of these peaks is relatively small and their existence of these on the F2 sample likely have to do with the lack of a ground plane layer to ensure better return/decoupling on the output capacitor. The performance mismatches of P4 can be broadly split into two: the set point mismatch when unloaded and then the sawtooth behaviour when loaded in excess. The voltage set point offset to 1.42 V instead of 1.3 V is thought to be caused by additional resistance introduced by suboptimal bonding between the feedback resistors and the silver epoxy. It is not believed to be a tolerance error as the resistors used had a tolerance of 1% which in the worst case scenario, would result on an output voltage of 1.33 V. The sawtooth behaviour appears to be the result of stress on the circuit. Given the results of the thermal testing (showing sawtooth pattern when unloaded), suggest that passing those higher currents during the electrical loading tests could have permanently impacted the circuit. It is not thought that the chip got damaged, but instead a thin or poorly plated trace. When passing those higher currents though that equivalent small trace it could have heated too much enough to deform the trace and alter the conductivity. Because of the oscillatory nature of the output voltage, following this broken trace theory, the affected trace could be one of the 2 traces connecting the output capacitor (C16). Despite this, the 3D printed circuit was proven to be able to deliver a fair amount of wattage (sufficient to actuate the intended burn-wire) without the use of larger copper polygons.

Preliminary thermal testing did not appear to have any effect on F2. When it comes to P4, the behaviour appears to be different before and after the thermal tests. However, this is believed to be a product of the electrical loading testing and not the thermal testing. No visible cracks, defects or delamination were identified on either of the samples. To further investigate the effects of uneven shrinkage on the 3D printed samples, longer, repeated thermal cycling should be performed.

4.2 Human-space environment evaluation

This work showed the technical feasibility of this methodology to produce functional, conformal, SMD circuitry. However, for its use in space, it is required to evaluate the suitability of such a process in a human-space environment and how it would fit within an astronaut workflow.

4.2.1 System evaluation

The overall methodology can be split into three different steps, each of these taking happening within a different part of equipment and materials, these are shown on Figure 15.



Figure 15 System overview and materials required.

In terms of equipment, the system is a couple of orders of magnitude less complex than other in-space 3D printing electronics solutions. The main reason is because these systems are more focused on microelectronics and component fabrication than substrate and circuit fabrication. The lower complexity of this system means that it is easier to operate, requiring

less training and being more accessible to the entirety of a mission's crew (as it is essentially regular MEX 3D printing with a couple extra steps). The lower complexity means tat the system is cheaper, easier to fix and easier to maintain. On the other hand, the system is more limited when it comes to printing scale, resolution and repeatability, but for the larger scale circuitry this system proves to be significantly more advantageous. Lastly, the number of different types of materials required to produce circuitry is relatively low (not including components), requiring only PLA, Electrifi, Electrodes, plating solution and conductive epoxy.

The main bottleneck of such a system is definitely the component assembly, as in the proposed solution it is done manually. The reason it was done manually is due to the conformality of the substrate and the bonding method, which make it incompatible with traditional pick-and-place machines. The use of epoxy for bonding makes the process more time consuming, more error prone and less reversible. This is not a unique issue to this system and in general cold-bonding for electronics is a highly relevant research area.

Nevertheless, the low complexity of such an approach poses high benefits that inherently make the on-demand fabrication of electronics circuitry more resilient, and in turn making space missions more resilient too.

4.2.2 Example use case and workflow

The following section provides and example situation during a space mission where the proposed system would highly enhance mission resilience. In this specific scenario, this is achieved through in-mission upgrades, which allow the crew to achieve higher scientific return. The scenario uses an example where conformality is highly desired, but the system is not limited to these curved structures.

"A settlement on mars is currently studying the low-density Martian atmosphere, they are interested in producing and testing Martian aircraft. They have spent the first few months of their mission performing measurements and now have a good understanding on the density, winds and other Martian atmospheric events. Thanks to generative design they were able to produce a variety of optimised small aircraft designs and would like to start trialling these on a real-life scenario. For this reason, they will be making use of their multi-axis, multi-material MEX 3D printer to produce aerodynamic surfaces with highly integrated on-board electronics on the structure. They were able to test a variety of designs, iterate a couple of times and achieve a highly efficient Martian aircraft design. Thanks to the ability to produce these lightweight, highly integrated, functional, conformal structures they were able to produce a large swarm of Martian aircraft which now image the surrounding areas and produce really valuable scientific data for future ore extraction and settlement determination."

With the understanding on how this system can fit within a space mission, the remaining part of this section will outline what the workflow would look like for an astronaut using the proposed system.

The whole system would exist inside a human habitat and for astronauts to use. First it would require the design of the circuit from an electrical point of view, this design would then be laid out within a highly integrated CAD tool, automatically projecting onto the target geometry the traces and pads. The CAD design could be done from Earth and sent to the crew to print or entirely developed by the crew on-site. The G-code for the target design would be easily generated requiring minimal intervention from the astronauts (as with current commercial slicers). The astronaut would then load the machine and print the parts. After printing, they would perform a visual inspection on the deposited traces, aiming to



Figure 16 AI generated (Sora) depiction of proposed scenario.

find open or short circuits. If the print was to fail it could be re-printed (settings could be adjusted if deemed required). A successful print would then be taken to be electroplated, in a low-gravity plating bath enclosure. After even plating, the astronaut would then perform an electrical test to ensure there have been no shorts from copper deposition on adjacent pads and traces. Lastly, the astronaut would have to manually place and bond the components using conductive epoxy. After curing, they can be tested and qualified for their respective space applications.

As seen, after printing, the process becomes relatively involved, requiring the astronaut to manually perform tests, plating and assembly. Despite this, it is acceptable for the low-volume high-variety, prototyping and repairing activities an astronaut would encounter. The authors believe it is possible to optimise this system to be more integrated and automatic, without increasing a significant increase in complexity.

5 Conclusion and Future Work

In conclusion, this work has demonstrated the ability to produce complex conformal circuitry using multi-material, multi-axis MEX and electroplating. It has been proposed and demonstrated the use of small multi-material bridges as a lightweight way to address miniaturisation on 3D printed electronics. The physical dimensions of the printed parts were evaluated and compared among samples. The electrical performance of the 3D printed circuit was compared against a FR4 PCB benchmark and showed the ability to regulate and deliver current. The printed part showed more noise and less reliable behaviour but demonstrated the ability of this method to produce conformal rigid complex functional circuitry. Overall, it was demonstrated how a lower complexity, lower cost method such as multi-material MEX could be used as an alternative to other electronics, in-space manufacturing methods. This work presents a proof of concept and its real-world, in-space implementation requires a more careful examination to the underlying processes. Future work should look at a more extensive/complex circuit characterisation, more reliable ways to miniaturise 3D printed circuitry (bridges) with the ultimate goal of increasing reliability and repeatability in MEX 3D printed electronics.

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Navigating Exoplanetary Systems in Augmented Reality: Preliminary Insights on ExoAR

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Abstract

With thousands of exoplanets now confirmed by space missions such as NASA's Kepler and TESS, scientific interest and public curiosity about these distant worlds continue to grow. However, current visualization tools for exploring exoplanetary systems often lack sufficient scientific accuracy or interactive features, limiting their educational effectiveness and analytical utility. To help address this gap, we developed ExoAR, an augmented reality tool designed to offer immersive, scientifically sound visualizations of all known exoplanetary systems using data directly sourced from NASA's Exoplanet Archive. By leveraging augmented reality's strengths, ExoAR enables users to immerse themselves in interactive, dynamic 3D models of these planetary systems with data-driven representations of planets and their host stars. The application also allows users to adjust various visualization scales independently, a capability designed to aid comprehension of comparative astronomical properties such as orbital mechanics, planetary sizes, and stellar classifications. To begin assessing ExoAR's potential as an educational and analytical tool and inform future iterations, a pilot user study was conducted. Its findings indicate that participants found ExoAR improved user engagement and spatial understanding compared to NASA's Eyes on Exoplanets application, a non-immersive exoplanetary system visualization tool. This work-in-progress paper presents these early insights, acknowledges current system limitations, and outlines future directions for more rigorously evaluating and further improving ExoAR's capabilities for both educational and scientific communities.

2012 ACM Subject Classification Human-centered computing → Scientific visualization

Keywords and phrases Immersive Analytics, Data Visualization, Astronomy, Astrophysics, Exoplanet, Augmented Reality, AR

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1 Introduction

In recent decades, efforts like NASA's Kepler [6] and TESS [26] missions have led to advancements in planetary astronomy through the identification of thousands of exoplanets orbiting distant stars. These discoveries have sparked considerable scientific interest and widespread public fascination, prompting fundamental questions about the characteristics and behaviors of these distant planetary systems. Although NASA's Exoplanet Archive [20] provides comprehensive and scientifically vetted exoplanetary data, existing tools for visualizing these systems often either incorporate artistic interpretations or are constrained by the limitations of conventional 2D displays. As a result, such approaches can limit the scientific accuracy of these visualizations or hinder a users' ability to accurately understand the complex 3D

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spatial relationships within them. In turn, such traditional approaches can inadvertently lead to misconceptions or incomplete understandings of the physical and orbital characteristics of their celestial bodies.

As extended reality (XR) technologies, encompassing both virtual reality (VR) and mixed reality (MR) [19], continue to evolve, their unique offerings present new opportunities for immersive scientific visualization and data analysis. These technologies can be particularly well-suited for representing complex 3D spatial relationships, as unlike traditional non-immersive methods, XR environments allow users to physically navigate and interact with data in 3D spaces. When compared to non-immersive methods, this has been shown to offer benefits like improved spatial comprehension and increased user engagement for a variety of data analysis tasks, especially for multidimensional and 3D spatial data [3, 8, 11, 12]. As a subset of MR, augmented reality (AR) technologies superimpose digital content onto the user's view of the physical world, enabling interaction with virtual elements while maintaining one's real-world awareness. In contrast to VR, this spatial and situational awareness allows users to explore and manipulate 3D visualizations without the risk of colliding with physical obstacles – an issue shown to hinder a user's ability to interact with and navigate through data during immersive analysis tasks [13, 15, 29]. These qualities make AR especially promising for visualizing exoplanetary data, as understanding orbital configurations, planetary scales, and system dynamics may similarly benefit from such immersive representation. Doing so is aimed to not only offer educational benefits, but also help support deeper scientific inquiry by enabling more intuitive exploration of complex, astronomical datasets.

To explore these possibilities, we developed ExoAR, an AR application designed to provide dynamic and empirically sound visualizations of all known planetary systems, encompassing both our Solar System and the thousands of confirmed exoplanetary systems orbiting distant stars. It generates these using data directly sourced from NASA's Exoplanet Archive, allowing both space enthusiasts and scientists alike to explore data-driven representations of known exoplanets orbiting their host stars in immersive 3D. Users can spatially interact with and manipulate these visualizations, adjust individual scaling factors to highlight different spatial and temporal characteristics of interest, and access the numerical data underlying each visualization.

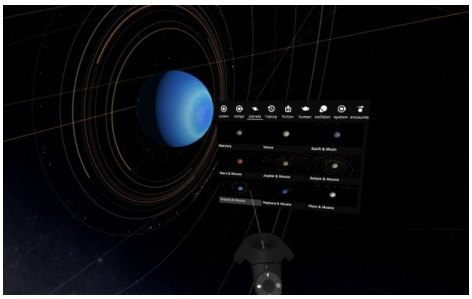
In this work-in-progress paper, we present an overview of ExoAR's system design, implementation, and formative evaluation through a pilot user study. Using NASA's Eyes on Exoplanets [21] as a comparative baseline, the study gathered user feedback and usability insights to inform iterative design improvements and assess ExoAR's relative ability to support accurate understanding of system-specific characteristics and spatial relationships. Our initial findings highlight both strengths and limitations of the current system, providing initial insights into the educational and analytical potential of AR-based exploration of exoplanetary data. We conclude by outlining directions for future development and more rigorous evaluation of ExoAR to further understand AR's potential for advancing space education and research.

2 Related Work

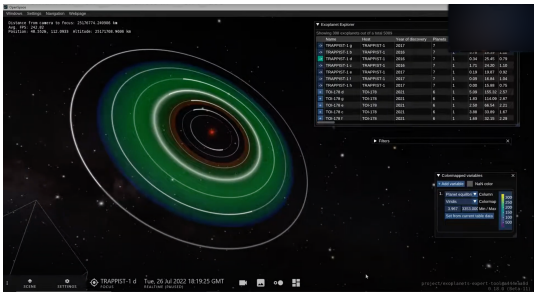
As exoplanet discoveries have grown over recent years, so too has the demand for accurate, interactive, and intuitive visualization tools to understand and communicate astronomical phenomena. Several modern tools currently exist both within and outside of academia that attempt to address this demand, though each faces distinct limitations that constrain their scientific accuracy, educational utility, or immersive interactivity.



(a) A screenshot of NASA's Eyes on Exoplanets web application showing the TRAPPIST-1 system [21].



(b) A user's VR view while using Universe Sandbox VR [2].



(c) A screenshot of OpenSpace being used to visualize the TRAPPIST-1 system [4].



(d) Microsoft's Galaxy Explorer AR demo app for learning about our Solar System [17].

Figure 1 Four examples of existing planetary system visualization tools using conventional (left) and XR (right) technologies.

2.1 Public Tools for Planetary System Visualization

Among publicly available software, NASA's Eyes on Exoplanets [21] (see Figure 1a) represents one of the most widely recognized and scientifically grounded tools. Leveraging data from NASA's Exoplanet Archive, it provides three-dimensional visualizations of known exoplanetary systems through a standard two-dimensional desktop interface. However, its interactive capabilities remain limited, as users cannot freely navigate or engage with models in a spatially immersive manner. Viewing complex three-dimensional planetary architectures on a flat screen often hinders spatial comprehension and makes it difficult to intuitively interpret orbital mechanics, planetary scales, or relative separations. This lack of embodied interaction may limit both its educational effectiveness and its value for scientific exploration.

Other notable tools, such as Universe Sandbox 2 VR [2] and Microsoft's Galaxy Explorer AR [17], have attempted to harness the immersive capabilities of extended reality technologies for astronomical visualization. Universe Sandbox 2 VR (see Figure 1b) offers dynamic simulations of celestial events in a fully immersive environment, but its focus remains on Solar System phenomena and its visualizations often prioritize interactivity and user experimentation over scientific precision. Similarly, Microsoft's Galaxy Explorer AR (see Figure 1d) presents holographic representations of planets and stars, yet also concentrates on Solar System content and contains simplifications in orbital dynamics and scaling accuracy. Neither platform incorporates scientifically validated exoplanet data in a form that enables detailed spatial analysis or exploratory learning. As such, both fall short of meeting the growing need for immersive, data-accurate exoplanet system visualization.

2.2 Academic Tools for Planetary System Visualization

Within academia, more advanced astronomy visualization frameworks have emerged, offering tools for exploring large-scale cosmic datasets. For example, software like Gaia Sky [27] and OpenSpace [5] (see Figure 1b) support interactive 3D visualizations of astrophysical data, including exoplanets in some cases, but remain largely tied to screen-based environments. A more recent system by Broman et al. [7] demonstrated high-fidelity exoplanet renderings enriched with contextual scientific information, yet their application similarly relies on conventional desktop displays and lacks immersive or embodied interaction capabilities. As Lan et al. [14] emphasizes in their comprehensive survey though, most astronomy visualization tools continue to be confined to traditional screens, limiting users' ability to engage meaningfully with spatially complex content.

2.3 XR for Astronomy Education & Visualization

More and more, however, XR technologies are being recognized for their potential to enhance astronomy education and spatial reasoning. Prior studies have demonstrated that immersive environments can support deeper conceptual understanding by reducing perceptual distortion and enabling embodied interaction with abstract phenomena. For instance, Antoniou et al. [1] reported that students using an AR-based astronomy application showed improved motivation and spatial understanding compared to those using traditional resources. Kersting et al. [10] similarly found that VR-based visualizations helped learners intuitively grasp cosmic distances and object scale. Broader reviews further support these results, suggesting that XR can improve learning outcomes in spatially demanding domains such as astronomy and geoscience [23, 25].

Despite this promise, relatively few XR applications have focused specifically on exoplanetary systems. The Exoplanets–A project by Peralta et al. [24] introduced a mobile AR application that allowed users to view simplified exoplanet orbits in educational contexts, while PlanetariumVR offers guided tours of selected exoplanet systems but limits user agency and scientific detail [9]. These efforts mark initial steps toward immersive exoplanet learning, yet no platform to date has successfully integrated validated exoplanet data with freeform, interactive XR exploration.

2.4 Addressing Current Gaps with ExoAR

This range of prior works highlights several gaps that ExoAR seeks to help address. Such existing tools either lack immersive interactivity, restrict user navigation, or rely on inaccurate data or artistic interpretations. Meanwhile, academic research into XR-supported astronomy education remains limited on how well it aids understanding complex exoplanetary systems and rarely incorporates rigorous evaluation. By combining scientifically accurate archival data with immersive exploration and an intuitive AR interface, ExoAR seeks to fill this void and contribute new insights into how immersive technologies can support conceptual learning and spatial reasoning in exoplanet science and education.

3 ExoAR: System Description

ExoAR is an AR tool designed to support the 3D visualization and immersive analysis of all currently known exoplanetary systems. Each is generated using validated astrophysical datasets from NASA, allowing for scientifically based representations of known exoplanets, their orbits, and their host stars that aim to be as accurate as the available data allows.

ExoAR's design targets two primary user groups: space enthusiasts and educators, who benefit from visualizations that simplify complex astronomical concepts, and scientific researchers in space-related domains, who could potentially utilize ExoAR for exploratory data analysis and hypothesis generation. As such, its design prioritizes usability, and interactive features, such as hands-on interactions and dynamic scaling controls, were purposefully implemented to help reduce user cognitive load and improve its educational effectiveness. Additionally, ExoAR's underlying architecture was structured to adapt to dataset changes, allowing for seamless adaptation to updated data or new exoplanet discoveries, ensuring its sustained relevance as our scientific understanding of exoplanets progresses. Built using the Unity engine [28], ExoAR targets support for the Meta Quest 3 [16] and Microsoft HoloLens 1 and 2 [18] due to their immersive capabilities, hands-on spatial interaction support, and widespread accessibility.

3.1 Data Collection & Preparation

ExoAR's visualizations are constructed using carefully curated data sourced directly from NASA's Exoplanet Archive. This authoritative database is comprehensive, containing data for over 5,800 confirmed exoplanets and their host stars, each with over 350 associated parameters. Given its extensive scale, significant pre-processing was necessary to maintain efficient real-time performance. To ensure scientific integrity for the visualizations, ExoAR reduced this dataset to eighty-four key parameters deemed most crucial for effective and accurate visualization. These included those related to planetary radii, masses, orbital periods, eccentricities, semi-major axes, equilibrium temperatures, stellar radii, spectral types, and effective temperatures. Uncertainty values for these critical parameters were retained as well, so the data's scientific precision could be presented transparently to users when viewing it in a system's information menu (see Figure 4). Subsequent dataset filtering involved splitting planetary and stellar data into separate datasets and systematically combining redundant entries when necessary by keeping the most recent value of any that differed between duplicates.

3.2 Technical Implementation & Key Features

Using astrophysical formulae, ExoAR translates this refined exoplanet dataset into science-driven exoplanetary system visualizations through the following key features, each designed to balance scientific rigor with user interactivity and understanding. These include dynamic 3D data visualizations of celestial bodies, independent controls for adjusting core spatial and temporal scales, and hands-on menus for accessing all systems and viewing their underlying data.

Dynamic Visualizations of Planetary System Data

ExoAR accurately represents the relative sizes of host stars and planets based on NASA's radius and mass data. When explicit radii were unavailable, astrophysical approximations based on stellar or planetary masses and densities were employed. Specifically, stellar radii were approximated using mass-density relationships relative to our Sun when necessary. Similarly, planets were classified into density categories based on their mass: rocky terrestrial planets, gas dwarfs, and gas giants, approximating their radii accordingly. This ensured visualizations remained empirically sound even when the data was only partially complete.

Planetary orbits within ExoAR are dynamically visualized using validated orbital parameters, including periods, semi-major axes, and eccentricities. For incomplete data, Kepler's Third Law was carefully applied to calculate missing values, ensuring orbital paths remained

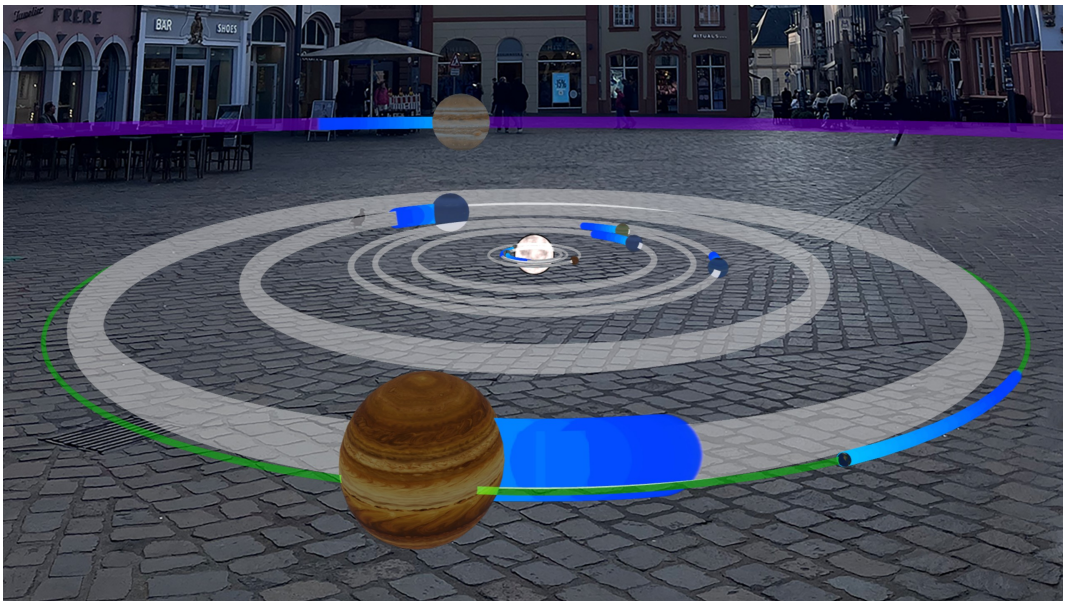


Figure 2 A visualization of the KOI-351 system using ExoAR in a large open space. The relative planet sizes are scientifically accurate, while the scaling of the host star, planets, and orbital distances have been adjusted individually so the user can more easily see the planets and their sizes relative to each other. Note Earth (green orbit) & Jupiter (purple orbit), have been toggled on into KOI-351 as a scale reference.

accurate reflections of current astrophysical understanding. Planets missing eccentricity values were assigned circular orbits, reflecting known statistical prevalence. The resulting visualizations enable users to immersively observe planets as they orbit, a feature aiming to aid conceptual understanding of orbital mechanics and system configurations.

ExoAR also aims to more accurately represents host star colors based on effective temperature data. Utilizing established astrophysical formulas derived from the Planckian locus on the CIE 1931 Chromaticity Diagram [22], ExoAR converts stellar effective temperatures into precise RGB color representations on the visible spectrum. When effective temperature data was absent, spectral classification served as a reliable proxy. This attention to visual accuracy further supports ExoAR's goal for educational authenticity and helps facilitate comprehension of common stellar properties.

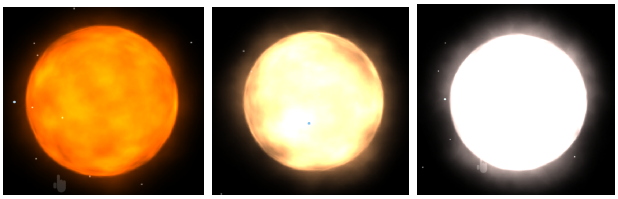


Figure 3 Three examples of different host stars in ExoAR. Their differing colors are a direct result of each star's different effective temperature, determining the color of their emitted light.

Independent Data Scaling & User Controls

Recognizing the challenge posed by astronomical scale disparities, ExoAR provides customizable scaling options across four key dimensions: planetary size, stellar size, orbital distances, and temporal scaling of orbital motion. These independent scaling controls allow users to

dynamically adjust visualizations according to their learning or analytical objectives. This flexibility seeks to remove confusion which can be introduced when multiple dimensions are linked and forced to stretch or shrink together in astronomical plots. For example, orbital scaling can compress vast interplanetary distances into manageable spatial contexts while planets can stay visible, or temporal scaling enables precise observation of planetary orbital periods at varying speeds. Users also have the option to temporarily freeze visualizations, allowing them to observe the data at specific moments in time.



Figure 4 An overview showing ExoAR's various features, with the Trappist exoplanetary system visualized for the user (center). Its three core menus are positioned around the system for easy access to data and customization. These are its main menu (bottom), System Info Menu (left), and System Search Menu (right).

Interactive Menus & Information Displays

To access all such features, ExoAR incorporates spatial AR menus, with the toggleable main menu always positioned centrally just below the user's natural line of sight (see Figure 4). This main menu allows users to adjust scaling factors, pause or resume planetary motions, and insert two reference planets into the system: Earth and Jupiter. By showing these familiar planets alongside others, this feature provides crucial references for comparing planetary data against those more well-known ones in the aim of aiding comprehension of unfamiliar astronomical scales and distances. This main menu also provides access to the two other menu panels (see Figure 4). First, the System Search Menu lets users browse for and select any exoplanetary system they wish to visualize. The other menu, the System Information Menu, aids system-specific understanding by displaying the exact numerical values underlying a system's visualization, revealing to users how the raw data maps to the AR rendering. Here, orange text indicates any values derived not from the raw data but via astrophysical calculations, providing users with a transparent means to identify which aspects of a visualization are scientifically approximated.

4 Pilot User Study

To begin evaluating ExoAR's potential as an educational and exploratory tool for visualizing exoplanetary systems, we conducted a qualitative pilot study. The primary objectives of this initial evaluation were to assess the system's usability, explore user perceptions regarding ExoAR's effectiveness compared to comparable non-immersive system visualization tools, and gather preliminary insights into how an AR approach might influence understanding and engagement while learning about exoplanetary systems.

4.1 Procedure & Task

Each participant took part in a one-hour, one-on-one session that began with a brief demographic and self-assessment questionnaire covering age, academic background, and their self-rated level of knowledge in physics, astrophysics, and exoplanetary systems (see Figure 5). Participants then received a five-minute orientation to the HoloLens and its hand-gesture controls, covering essential interactions such as how to press AR buttons or grab and move AR objects. Next, they spent fifteen minutes in ExoAR, starting with a five-minute guided walkthrough of its core features to ensure all participants had experience with and knew how to use all of them. These introductory tasks started with participants using the main menu to scale planetary and stellar sizes, adjust orbital and temporal scales, and insert Earth and Jupiter reference planets into the current system. They then used the System Information Menu to view the system's data, and lastly, used the System Search Menu to switch to a different system. Once complete, participants had the remaining ten minutes to freely use ExoAR as they wished. Participants then repeated the same sequence with NASA's Eyes on Exoplanets, with five minutes of structured introductory tasks and ten minutes of unstructured use, to establish a non-immersive baseline.

Upon completing the fifteen-minute sessions for both tools, participants filled out a structured survey comparing the two tools' effectiveness at conveying exoplanetary concepts. Through its questions, participants indicated which tool they felt better conveyed exoplanet system concepts and described where ExoAR excelled or fell short for this. Next, they explained which tool was their overall preference for learning about exoplanets before reflecting on whether ExoAR affected their learning experience and if they learned anything new while using it. Lastly, they offered feedback on their favorite ExoAR features, aspects in need of improvement, and suggestions for future additions.

4.2 Participants

In total, eight University of Calgary undergraduate students volunteered to participate in the pilot study, all aged 20 to 30 years old ($\bar{x} = 23.5$, $\tilde{x} = 22.5$). They were assigned identifiers P1–P8 in ascending order of their self-reported domain knowledge, determined by combining weighted ratings of their current knowledge in physics, astrophysics, and exoplanetary systems (see Figure 5). Distributed across the mechanical engineering, physics, and astrophysics fields, these participants' differences in astronomy and exoplanet knowledge allowed us to capture feedback from various levels of domain familiarity. No participant had previous experience with ExoAR, NASA's Eyes on Exoplanets, or the Microsoft HoloLens, guaranteeing fresh impressions of the AR hardware and both tools.

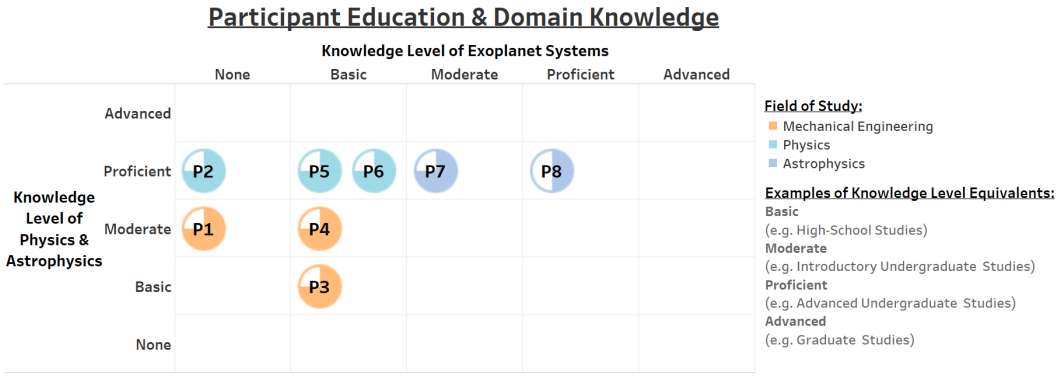


Figure 5 Pilot participants P1–P8 plotted by their self-rated levels of physics and astrophysics knowledge (y-axis) and exoplanetary systems knowledge (x-axis). Circle color denotes their field of study, and for in-progress studies, its fill fraction shows their progress by degree quartiles completed.

4.3 Results

Initial qualitative feedback on ExoAR revealed promising insights into ExoAR's usability and educational potential. Most notably, when asked to compare ExoAR's immersive approach to NASA's Eyes on Exoplanets for visualizing planetary systems and learning about exoplanetary concepts, every participant preferred ExoAR. Upon analyzing their other feedback, three dominant themes emerged to help explain this unanimous preference.

First, nearly all participants (P1–P5, P7) appreciated how ExoAR's immersive 3D experience made it easier to navigate the system visualizations and view their elements from different perspectives. This was for all three methods of viewpoint navigation: physically walking around, adjusting distance scales, or by using a pinch-and-drag gesture on its host star to move the system where desired. For example, P3 voiced that "standing in it and walking around" or "being able to move around and drag a system closer or further is much more intuitive". Second, four participants (P1, P3, P6, P7) reported that ExoAR's 3D immersion was a more intuitive experience for grasping the relative sizes, distances, and orbits between celestial bodies. P1 explained that being immersed gave them "a better physical sense of the systems", while P6 shared they found it comparatively easier for "understanding the speed of some of the orbits, how wide planets are, and the distance between some of the planets". Even P7, an astrophysics student, stated this "really helps for scale, especially if someone is unfamiliar with the massive scales of space". Third, many participants (P1, P4, P6, P7) also reported that ExoAR's immersion and hands-on approach made learning about exoplanets a more engaging and enjoyable experience. For instance, ExoAR was said to be "a video game with the side effect of learning" (P1), that it made for "a cooler and more memorable experience" (P7), with AR having a "large impact" (P4) that made the experience "far more interesting" (P4).

Supporting these themes, four participants (P1, P3, P4, P7) specifically praised ExoAR's independent size, distance, and time scaling controls, which they found contributed to a better experience than when using Eyes on Exoplanets. P1 said "I found NASA's hard to navigate without the scalability", but they felt this feature of ExoAR "made the experience better as it allowed for exploration outside of the arrangement" that Eyes on Exoplanets keeps a user's view to. Echoing this, P3 thought that "Eyes on Exoplanets lacks any physical scale", but in ExoAR they could "easily scale planets and pan them, which is a large benefit". In addition, participants P1, P2, P3, and P6 pointed out they valued the ability to use Earth

and Jupiter as a familiar size and distance reference. This was explained well by P6, who shared "being able to compare to Jupiter and Earth gave me a frame of reference I didn't have" with Eyes on Exoplanets, which helped them and others to anchor their sense of scale between otherwise confusing sizes and distances.

Despite this mostly positive feedback, participants also identified several areas for improvement. Five participants (P1, P3, P5–P7) experienced issues stemming from the limitations of the HoloLens hardware, namely its restricted field-of-view, relatively lower graphical fidelity, and occasional input lag. The main menu's placement below eye level was also problematic to some (P2, P3, P4), who complained that due to its position "one must look down often" (P2) and it can sometimes be "difficult to find" (P4). Two participants (P6, P8) noted that NASA's software felt more polished and feature-rich, an expected gap for ExoAR as a prototype. Despite these critiques, when asked to consider their overall experience for tasks shared across both tools and choose one tool to continue using for further learning, all but one chose ExoAR, each pointing to one or more of the aforementioned themes as their primary reason. P8 was the sole exception, who noted that despite preferring ExoAR's immersion for analyzing planetary data in 3D, due to its current technical limitations they would rather use Eye on Exoplanets until ExoAR became more polished and its feature set more closely matched that of NASA's tool.

5 Discussion

5.1 Preliminary Insights

The findings of this formative pilot suggest ExoAR's approach to using AR for the scientific visualization of exoplanetary systems shows promise for enhancing user engagement and data comprehension. Overall, participants reported that ExoAR's immersive approach allowed them to be more engaged with the system visualizations, had an easier time viewing them from different perspectives, and that being immersed within a system felt more intuitive for understanding relative celestial object sizes, distances between orbits, and orbital speeds compared to Eyes on Exoplanets. Such insights suggest that the immersive 3D experience, physical spatial navigation, and hands-on interactions commonly supported by AR and other XR technologies may help address some challenges traditionally difficult to overcome when using non-immersive visualization techniques. ExoAR's independent scaling feature also emerged as particularly beneficial, with participants reporting that the ability to adjust planetary, stellar, and orbital scales separately made it noticeably easier to understand interplanetary relationships, orbital mechanics, and comparative planetary sizes. The ability to insert Earth and Jupiter as reference planets in a system was also said to aid understanding. It it important to note, however, that these features do not require AR or immersive technologies, suggesting they may be a useful addition for non-immersive system visualizations as well.

Room for improvement was also identified by participant feedback. Most commonly noted was participants citing usability concerns stemming from the HoloLens' hardware constraints. While external to ExoAR's software, these limitations negatively impacted user perception and highlight the need to either explore other XR hardware or optimize the visualizations' complexity for the HoloLens' limitations to maintain smooth, immersive interactions and minimize cognitive distractions. Furthermore, feedback on interface usability was mixed. While most found the design intuitive, others noted that the main menu's placement disrupted immersion and increased cognitive load. Thus, future iterations should refine the main menu's placement and design, and also explore gaze- or gesture-based interaction modalities to improve usability and maintain user engagement.

These useful preliminary insights highlight the importance of iterative design processes informed by user-centered evaluation, particularly when integrating novel visualization technologies into educational and research contexts. The feedback gathered in this pilot study will directly inform our planned improvements, which will focus on both technological and usability enhancements. Future research will benefit from systematically evaluating ExoAR's impact more rigorously and across more varied demographics to assess how differences in prior exoplanet knowledge, familiarity with AR technologies, and past education may influence the tool's effectiveness for learning and data analysis.

5.2 Limitations

While useful for guiding ExoAR's future development and evaluation, as a formative pilot study, we acknowledge limitations of its findings. First, due to the pilot's small, qualitatively evaluated sample, it findings cannot be generalized beyond initial user experiences. Although varying somewhat, the sample was still relatively homogenous in age, educational background, and prior exoplanet knowledge, which limits its generalizability to others like planetary researchers or older users. Short exposure to both XR and traditional systems also made it difficult to assess if learning curves or long-term use had any impact on opinions. Additionally, novelty effects from participants' overall lack of AR experience may have inflated perceived benefits. Despite such these limitations, these early findings still suggest ExoAR holds promise for effectively conveying complex astronomical concepts to at least some users, justifying its further development and future larger-scale evaluation.

6 Conclusion & Future Work

Aimed to help address current limitations with exoplanetary data visualization, we presented ExoAR, a work-in-progress augmented reality visualization tool designed to enhance understanding and exploration of exoplanetary systems using scientifically accurate data from NASA's Exoplanet Archive. Our pilot study provided preliminary insights into ExoAR's effectiveness, indicating promising educational benefits compared to traditional two-dimensional visualization tools. Participants reported notable improvements in engagement, spatial cognition, and improved comprehension of exoplanetary concepts, primarily due to ExoAR's immersive 3D visualization offerings, hands-on interactions, and independent scaling controls. Several key limitations emerged, however, notably usability challenges related to current AR hardware constraints and interface design considerations. Addressing these issues through iterative design improvements thus remains essential. Furthermore, the promising yet preliminary nature of the study underscores the necessity of conducting larger evaluations that both quantitatively and qualitatively assess ExoAR's educational impact more rigorously across more diverse demographics and use cases. Future iterations will prioritize technical optimization, user-centered design refinements, and robust empirical validation studies. By systematically addressing current limitations and expanding ExoAR's current capabilities, we aim to improve the accessibility and effectiveness of exoplanetary data analysis through its capabilities. Ultimately, ExoAR represents a potentially useful step toward improving scientific communication and education in astronomy, demonstrating the unique advantages of AR technology for visualizing and exploring the rapidly expanding knowledge of exoplanetary systems.

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Towards Passively Actuated Short-Range Telehaptics for Astronauts

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Abstract

Human extra-vehicular activity (EVA) plays a vital role in current and near future space exploration for two reasons: the superior dexterity exhibited by human astronauts, and their flexible problem-solving and decision-making capabilities. However, the dexterity of astronauts during EVA is limited by the flexibility and tactility of their EVA suit gloves, which are primarily designed to provide thermal insulation and pressure for the hand. This creates a compromise between utility and protection. To address this compromise, a Passively Actuated Short-range Telehaptic (PAST) device is proposed. The PAST device couples the motion of fingers between a robotic hand and a human hand through a hydraulically actuated linkage. It also transfers tactile information, including pressure, direction of motion, and position of contact, via a taxel array. Results demonstrate that the proposed prototype PAST device surpasses an unpressurised benchmark heavy work glove (HWG) in tasks involving tactile position and motion direction identification. This provides evidence supporting the feasibility of enhancing astronaut dexterity during EVA through the use of PAST devices as an alternative paradigm to gloves.

2012 ACM Subject Classification Hardware → Haptic devices; Computer systems organization → Robotic control; Human-centered computing → Haptic devices; Hardware → Sensor devices and platforms

Keywords and phrases Extra-vehicular Activity, Mechanism Design, Haptics, Dexterity, Tactility

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1 Introduction

Extra-vehicular Activity (EVA) by humans is a vital aspect of past, current, and near-future space exploration endeavours. EVA allows for crucial maintenance, repair, and scientific fieldwork, enabling safer and more ambitious missions in the challenging environment of space. Productive work during EVA has historically been limited to a maximum of 8 hours, primarily due to partial-pressure exposure constraints and human endurance limitations [12]. Various potential hazards to human health and life during EVA include, but are not limited to, extreme contact surface temperatures ($\approx -150°C$ to $150°C$), heightened radiation doses, chemical contamination, and micrometeoroids [12]. In protecting astronauts from these hazards, EVA suits dramatically impair dexterity, leading to a severe limitation on the number and complexity of EVA tasks that can be completed. The existing design requirements for EVA gloves have resulted in a compromise between protection and utility, a design


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approach that has remained largely unchanged since the 1970s [11]. Despite efforts, due to the inherent compromise between protection and utility, current gas-pressurised glove designs offer dexterity "[comparable] to that of heavy work gloves" [12] and remain the most common source of injuries among astronauts during spacewalks [1].

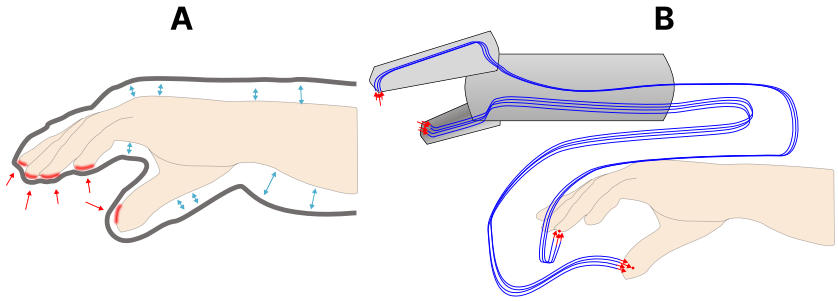

Figure 1 Image **A** illustrates the causes of loss of flexibility and tactility in conventional EVA gloves from thick insulation and the pressurised volume of the glove. The insulation diffuses precise points of pressure through the fabric. Image **B** illustrates the connection between the fingertips of the astronaut and the robotic hand via hydraulic channels that transfer tactile information to multiple points on each finger.

During EVA, astronauts engage in various tasks that require the manipulation of objects using tools or their own gloves. However, the stiffness of the gloves resulting from internal pressurization has significantly hampered hand dexterity [19] and contributed to hand injuries [1]. To enable improved dexterous manipulation, it is crucial to avoid inhibiting the astronaut's somatosensory system through high resistive forces or signal-diffusing insulation [16]. One proposed approach to deal with this degradation of dexterity from EVA gloves is an active stiffness-compensating exo-skeleton [15]. This decreases forces that the fingers of the astronauts repeatedly experience and may reduce injuries and improve dexterity through minimising fatigue. However, this solution would not significantly enhance tactility, while also creating potential injury-causing failure modes. A promising approach to improve flexibility and tactility of space suits is to apply mechanical counter-pressure (MCP) to the body rather than atmospheric pressure [17]. This would improve dexterity by increasing flexibility of the hands and reducing fatigue, by removing the 'air spring' for the fingers to work against. However, the requirements of insulative protection of the hands would still hinder tactility. MCP is at an early technology readiness level, despite being first proposed in the 1950s [10]. Currently, MCP systems struggle to achieve uniform pressure distribution, especially on concave sections of the body, and fail to ensure the same thermal contact insulation as incumbent solutions.

Certain mission-critical tasks can be accomplished remotely by leveraging telepresence (TP) [7], eliminating direct personnel risk by creating a layer of separation between the operator and potential hazards. This approach is used terrestrially for handling hazardous materials, such as radioactive samples, biohazards, and explosive devices. It can also be used with specialised tools such as in surgical TP robots to maximise performance of specific tasks [18]. However, TP may bring significant drawbacks with distance induced latency and lower mission flexibility [14]. Actuation and sensing limitations creating lack of responsiveness lead to a loss of dexterity. To address these drawbacks, short range solutions are favoured for minimising latency and information loss. Passively actuated or directly driven systems are favoured for responsiveness and minimising complexity.

Hydraulic-based passively actuated haptic systems are well suited to EVA. Hydraulic tele-haptic systems have been demonstrated for other applications, with the human-safe haptic TP robot providing a human user with precise force and position control of a humanoid *bibrachial* robot with instant feedback [21]. Hydraulic actuation as a paradigm for local teleoperation is becoming more attractive due to its possibility to be designed into high transparency mechanisms, providing high fidelity force feedback [6]. Passive sensory transfer has also been demonstrated through an air-mediated interface in application to arm prostheses, in order to transfer pressure from a robotic hand to the forearm of the user [2]. This approach is suitable for low fidelity signal feedback due to the compressibility of air, however incompressible hydraulics may be needed for high fidelity information transfer.

In this work, we propose a novel approach to improve astronaut dexterity without significantly increasing operational complexity, through passively actuated short-range tele-haptics (PAST). The proposed PAST approach includes an external hydraulically actuated mechanical hand attached to the arm of the user, connected to the user's hand and actuated via a linkage. The mechanical hand also houses a number of embedded hydraulic channels in the tip of each gripper finger, hydraulically connecting the fingertips of the external hand and the user's hand. The external mechanical hand enables the user's hand to be isolated from the real task, providing protection from hazards associated with EVA, while transferring haptic and tactile information.

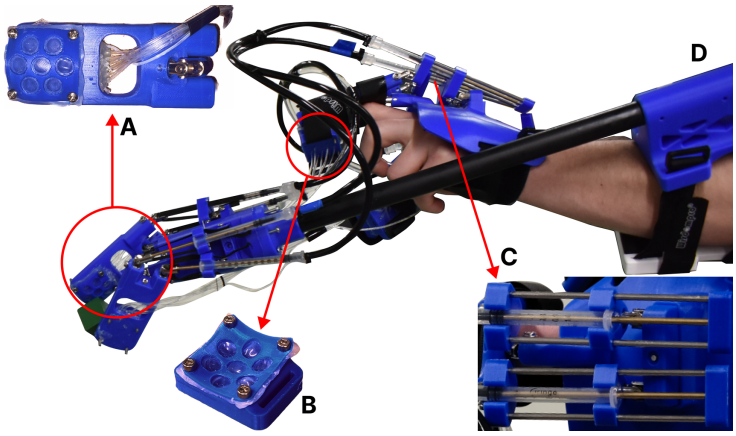

Figure 2 The PAST device being used to manipulate a small wooden block. The robot-side and human-side taxel arrays are visible in **A** and **B**, respectively. **C** shows the piston inversion mechanism, which enables the kinematically identical robot and human-side's hydraulic cylinders to have inversely proportional volumes, in order to result in a mimicking movement from the input and output. The robot arm is attached to the user's arm at **D**, and extended beyond the user's hand with a fiber-glass boom.

2 Design and Characterisation

2.1 Design Overview

The PAST device is designed to demonstrate simple manipulation and touch tasks and transmit the experience of tactile feedback. It is comprised of a human-facing hand interface and a robot hand which is mounted with an off-set on the users arm as seen in Fig. 2.

The PAST device has two principal subsystems: The haptic hydraulic linkage (HL), and the hydraulic taxel array (HTA). Both of these subsystems connect the human-facing hand interface and the attached robotic hand. Dexterous human manipulation relies on information

from the somatosensory system. Both shallow rapidly-adapting and deep slowly-adapting mechanoreceptors provide rate of skin indentation and depth of skin indentation information respectively [16]. The two subsystems provide input to stimulate both. Deep indentation from force feedback of grasping an object is provided by the HL, while the tactile information of specific position of contact, motion, and macro-scale texture are provided via the HTA.

This PAST prototype is designed to be manufactured with cheap and accessible materials, so as to allow rapid design iteration, and low-cost preliminary testing of the PAST concept. The HL uses proprietary $1ml$ syringes as hydraulic cylinders, and PVC tubing which are filled with silicone oil and connected to the syringes via a proprietary Luer lock secured with a zip-tie. Silicone oil was selected as the hydraulic fluid of the PAST device, due to its suitable thermal properties to withstand extreme hot and cold temperatures, and its prior use as a pressure distributor in MCP prototypes [20]. To ensure that the HL is rigid, the syringe plunger is replaced with a brass rod with a custom end-feature for securing the rubber plunger. The blue plastic components of the HL and HTA are 3D-printed, and secured with steel fasteners and superglue. The smaller $1mm$ internal diameter channels used for the HTA are also PVC, and secured in place first with guiding channels to push them into, and then with superglue and superglue accelerant to seal any gaps and secure them in place.

2.2 Haptic Hydraulic Linkage

The HL is designed to transfer the motion of the user's thumb and index finger to the robotic hand. The user's finger is constrained by a 2 degrees of freedom (2DoF) linkage that allows for flexion/extension and adduction/abduction motions. The motion of the finger determines the motion of two pistons, which hydraulically actuate two 'reversed syringes' on the robotic side. With the reversal of the syringes, the human-side and robot-side linkages are enabled to be kinematically identical as seen in Fig. 3.

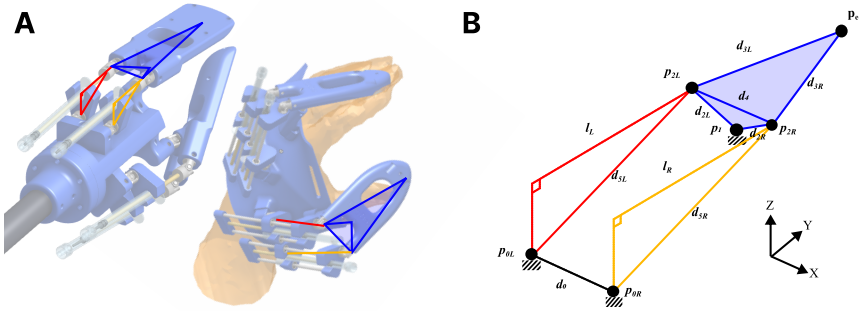

Figure 3 Image **A**: A kinematic diagram overlaid onto the design of the haptic hydraulic linkage (HL) gripper (left) and the HL hand interface (right) - illustrating their kinematic equivalence. Image **B**: The kinematic diagram of the HL, which is identical for both the human-facing and robotic side. The notation $\boldsymbol{p}_n$ denotes point vectors. Likewise, $\boldsymbol{d}_n$ denotes distance vectors which may change in direction but not magnitude, and $\boldsymbol{l}_n$ denotes the variable lengths of the pistons.

A two-fingered non-anthropomorphic design was chosen for the HL, allowing for the demonstration of grasping, while additional fingers would bring diminishing returns on what can be proven while increasing build complexity significantly. The thumb and index finger were chosen to be used, as they are the primary fingers used in manipulation. To mimic the relative position of the thumb and index finger, the two 2DoF fingers are offset at 135° relative to one another. The choice of two 2DoF fingers was done to mimic human-like pinch-grip

configurations, which rely on both the thumb and index being able to adduct/abduct. The possible relative configurations of two 2DoF fingers are very similar to having one 1Dof and one 2DoF finger, allowing the 2DoF finger to translate and rotate around the 1DoF. However, this would not reflect the way that the human manipulation with the thumb and index fingers is done.

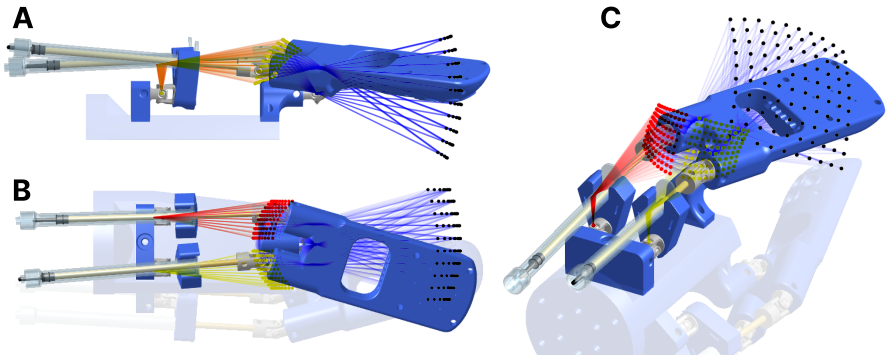

Figure 4 The kinematics can be used to generate a point-cloud of the workspace of an HL finger. The point-cloud and link positions are projected over an example position of the finger. **A** and **B** are orthogonal views, and **C** is an isometric view.

2.2.1 Forward Kinematics of the Robot Finger

The forward kinematics of the robot finger relate the length of each piston, $l_L^{(r)}$ and $l_R^{(r)}$ to the fingertip end-effector position $\boldsymbol{p}_e^{(r)}$ as seen in Fig. 3. Given that the finger is a rigid body, the rotation matrix $\mathrm{R}_e^{(r)}$ about the lower finger attachment joint is all that is necessary. We start by finding an expression for $\boldsymbol{p}_{2R}^{(r)}$, the position of the distal joint at the end of the right piston. $\boldsymbol{p}_{2R}^{(r)}$ lies on the intersection of two spheres: one centered on the proximal piston attachment point $\boldsymbol{p}_{0R}^{(r)}$ with radius defined by the vertical offset of the piston axis and the length of the piston $r_1^{(r)^2} = l_L^{(r)^2} + d_1^{(r)^2}$, and the other centered on the lower attachment point $\boldsymbol{p}_1^{(r)}$ with radius defined by a known initial offset $\boldsymbol{d}_{2R}^{(r)}$ such that $r_2^{(r)} = \left|\boldsymbol{d}_{2R}^{(r)}\right|$.

The intersection of two spheres is a circle with normal $\boldsymbol{n}_R^{(r)}$ pointing along the vector between the two centres of the spheres. The centre of the circle $\boldsymbol{c}_R^{(r)}$ is positioned along the vector between the sphere centres:

$$\boldsymbol{c}_R^{(r)} = \frac{\left|\boldsymbol{p}_1^{(r)} - \boldsymbol{p}_{0R}^{(r)}\right|^2 - r_2^{(r)^2} + r_1^{(r)^2}}{2\left|\boldsymbol{p}_1^{(r)} - \boldsymbol{p}_{0R}^{(r)}\right|} \cdot \boldsymbol{n}_R^{(r)}. \tag{1}$$

The radius of the circle $r_R^{(r)}$ can then be calculated:

$$r_R^{(r)^2} = r_1^{(r)^2} - \left|\boldsymbol{c}_R^{(r)}\right|^2, \tag{2}$$

and $\boldsymbol{p}_{2R}^{(r)}$ lies on this circle:

$$\left|\boldsymbol{p}_{2R}^{(r)} - \boldsymbol{c}_R^{(r)}\right|^2 = r_R^{(r)^2}. \tag{3}$$

Given that $\boldsymbol{p}_{2R}^{(r)}$ is equal to $\boldsymbol{p}_1^{(r)}$ plus the initial offset $\boldsymbol{d}_{2R}^{(r)}$ rotated around the lower attachment joint:

$$\boldsymbol{p}_{2R}^{(r)} = \mathrm{R}_e^{(r)} \boldsymbol{d}_{2R}^{(r)} + \boldsymbol{p}_1^{(r)}, \tag{4}$$

Which can also be written as a homogeneous transformation:

$$\boldsymbol{p}_{2R}^{(r)} = \begin{bmatrix} \mathrm{R}_e^{(r)} & \boldsymbol{p}_1^{(r)} \\ 0 & 1 \end{bmatrix} \boldsymbol{d}_{2R}^{(r)}, \tag{5}$$

an expression relating the rotation matrix $\mathrm{R}_e^{(r)}$ to the circle can be obtained:

$$\left| \mathrm{R}_e \boldsymbol{d}_{2R}^{(r)} + \boldsymbol{p}_1^{(r)} - \boldsymbol{c}_R^{(r)} \right|^2 = {r_R^{(r)}}^2. \tag{6}$$

Expanding and simplifying (6) yields:

$$2\left(\boldsymbol{p}_1^{(r)} - \boldsymbol{c}_R^{(r)}\right)^T \mathrm{R}_e^{(r)} \boldsymbol{d}_{2R}^{(r)} = {r_R^{(r)}}^2 - {r_2^{(r)}}^2 - \left| \boldsymbol{p}_1^{(r)} - \boldsymbol{c}_R^{(r)} \right|^2, \tag{7}$$

with an identical expression computed for the left-hand piston:

$$2\left(\boldsymbol{p}_1^{(r)} - \boldsymbol{c}_L^{(r)}\right)^T \mathrm{R}_e^{(r)} \boldsymbol{d}_{2L}^{(r)} = {r_L^{(r)}}^2 - {r_2^{(r)}}^2 - \left| \boldsymbol{p}_1^{(r)} - \boldsymbol{c}_L^{(r)} \right|^2. \tag{8}$$

Given that $\mathrm{R}_e^{(r)}$ is the compound of two rotations, and therefore there are only two unknown variables, equations (7) and (8) can be solved numerically to find the rotation of the finger about the lower attachment point.

2.2.2 Inverse Kinematics of the Human Finger

The inverse kinematics of the human finger relate the fingertip end-effector position $\boldsymbol{p}_e^{(h)}$ to the length of each piston, $l_L^{(h)}$ and $l_R^{(h)}$. Again, the finger is a rigid body, so the end-effector position determines the rotation of the finger about its lower attachment point $\mathrm{R}_e^{(h)}$:

$$\mathrm{R}_e^{(h)} \boldsymbol{d}_e^{(h)} + \boldsymbol{p}_1^{(h)} = \boldsymbol{p}_e^{(h)}, \tag{9}$$

Noting that $\mathrm{R}_e^{(h)}$ is comprised of sequential rotations about the z and x axes by θ_z and θ_x, respectively, (9) can be rewritten:

$$\mathrm{R}_{e,z}^{(h)}(\theta_z) \mathrm{R}_{e,x}^{(h)}(\theta_x) \boldsymbol{d}_e^{(h)} = \boldsymbol{p}_e^{(h)} - \boldsymbol{p}_1^{(h)}. \tag{10}$$

$\mathrm{R}_e^{(h)}$ takes the form:

$$\begin{bmatrix} c(\theta_z) & -s(\theta_z) & 0 \\ c(\theta_x)s(\theta_z) & c(\theta_x)c(\theta_z) & -s(\theta_x) \\ s(\theta_x)s(\theta_z) & s(\theta_x)c(\theta_z) & c(\theta_x) \end{bmatrix}, \tag{11}$$

where $c(\theta) = \cos(\theta)$ and $s(\theta) = \sin(\theta)$. The rotation about the z axis can be found by solving the x component of (10) for θ_z:

$$d_{e,x}^{(h)} c(\theta_z) - d_{e,y}^{(h)} s(\theta_z) = p_{e,x}^{(h)} - p_{1,x}^{(h)}. \tag{12}$$

Similarly, θ_x can be found by pre-multiplying (10) by $\mathrm{R}_e^{(h)T}$ and solving its z component for θ_x:

$$(p_{e,z}^{(h)} - p_{1,z}^{(h)})c(\theta_z) - (p_{e,y}^{(h)} - p_{1,y}^{(h)})s(\theta_z) = d_{e,z}^{(h)}. \tag{13}$$

There are four solutions to (12) and (13), from which the accepted solution can be chosen to maintain link length $|\boldsymbol{d}_e^{(h)}|$.

The location of the distal joint of the right piston can then be found from the rotation of the initial offset about the lower attachment point:

$$\boldsymbol{p}_{2R}^{(h)} = \mathrm{R}_e^{(h)}\boldsymbol{d}_{2R}^{(h)} + \boldsymbol{p}_1^{(h)}. \tag{14}$$

Knowing the positions of $\boldsymbol{p}_{0R}^{(h)}$ and $\boldsymbol{p}_{2R}^{(h)}$, and size of the perpendicular offset from the piston axis to its proximal attachment point $|\boldsymbol{d}_1^{(h)}|$, the length of the right piston $|\boldsymbol{l}_R^{(h)}|$ can be calculated:

$$|\boldsymbol{l}_R^{(h)}| = \sqrt{|\boldsymbol{p}_{2R}^{(h)} - \boldsymbol{p}_{0R}^{(h)}|^2 - |\boldsymbol{d}_1^{(h)}|^2}, \tag{15}$$

with an identical formulation for the left piston length $|\boldsymbol{l}_L^{(h)}|$.

2.2.3 Workspace

The workspace can be visualised by creating a point-cloud of end-effector positions computed via forward kinematics, as seen in Fig. 4. The dominant constraint of the workspace in practice is the range of motion permitted by the attached human finger, which will vary from user-to-user.

2.3 Hydraulic Taxel Array

The HTA transfers positional tactile information from the robotic hand to the finger-tips of the user. An HTA of 7 cells spaced 8 mm apart in a hexagonal grid is attached to each active finger via a finger interface, which is comprised of a fluid-filled channel with a molded silicone rubber bubble on both ends. These channels are routed through the plastic body of the robotic side to connect with thin 1.6 mm PVC tubing which in turn connects to the input points of the human-side finger interface as seen in Fig. 5. When the robotic-side bubble is deformed by applied pressure, it expands the human-side bubble, deforming the skin of the finger and transferring the feeling of touch. The user-side HTA is distributed around the fingertip, with the central taxel coinciding with the centre of the finger pad of the user.

The distance of 8 mm between the taxels was chosen firstly to simplify manufacturing of the prototype. However, this relatively large distance between each point approaches the limit of human two-point discrimination at the fingertip, which has been measured to be around $2 - 6$ mm [13].

2.3.1 Fabrication & Preparation

The taxel array was fabricated using a 'sandwich' structure, clamping a silicone membrane between the base-structure (the robot finger, or finger interface) and a 3D-printed plastic mesh as seen in Fig. 6. Once steel fasteners were in place to ensure that the silicone was under compression, superglue and adhesive accelerant were applied to the edges of the mesh and silicone structure, which sealed the edges, preventing leaks.

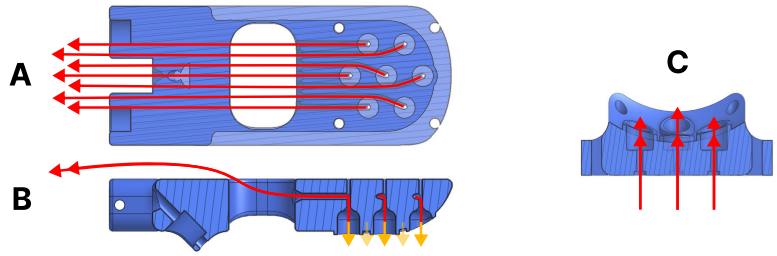

Figure 5 An illustration of the routing of hydraulic channels for the HTA. In **A** and **B** the channels of the robot side finger are shown, and how the pressure is transferred into the human side in image **C**. In **B** the narrow fill-points of each taxel which are designed for input with a needled syringe and easy sealing can be seen denoted by the yellow arrows.

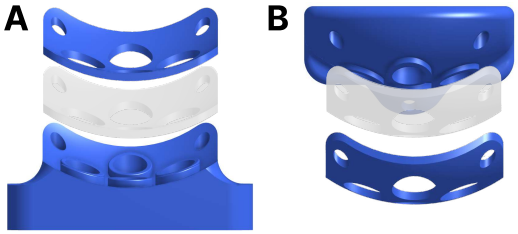

Figure 6 Image **A** and Image **B** show the taxel array fabrication, using a 'sandwich' structure of plastic and molded silicone rubber for the finger interface and robot finger, respectively. The curvature of the ergonomic finger interface is mirrored in the curvature of the robot finger. The holes on the corners of the clamping plastic mesh are to accommodate steel fasteners which allow for mechanical compression of the silicone layer, before sealing shut with adhesive.

In order to prepare the HTA, a narrow open channel for each taxel was included in the top of the robot-side finger, creating fill-points which can be accessed with a syringe and sealed with glue (denoted by yellow arrows in Fig. 5). This enables each taxel to be filled and sealed individually to the required initial pressure.

3 Performance Evaluation

3.1 Hydraulic Tactile Array Benchmarking

3.1.1 Positional Identification Methods

The identification of contact-points of the object being manipulated with the manipulator is an important factor of dexterous manipulation, and is the purpose of our somatosensory system [16]. In order to evaluate the tactility of the HTA against a heavy work glove (Fig. 7), 7 participants (1 female adult and 6 male adults) were asked to complete a blindfolded task of identifying which taxel or location on a heavy work glove (A, B, C, D, E, F, or G as in Fig. 9) was activated via a gentle depression with a soft rubber cylinder. The glove was selected as a benchmark due its tactile degradation being comparable to that of EVA glove [12]. The benchmark heavy work glove had an identical pattern to the taxel array marked onto it to ensure consistency in the relative positions of the pressure applications. To lighten the mental load for participants, a clock-face analogy was used to identify the 7 taxels, with [A, B, C, D, E, F, G] corresponding with [12'oclock, 10'oclock, 2'oclock, centre,



Figure 7 The benchmark heavy work glove with markings for input positions on the index finger (left), and the two-fingered human-side interface (right) used for testing the sensitivity to motion and positional pressure.

8'oclock, 4'oclock, and 6'oclock] (Fig. 8). In order to nullify the effects of learning in this study, participants were given the glove or taxel in a random order, in addition to the order of depressed location being randomised for both the glove and HTA.

3.1.2 Motion Direction Identification Methods

Sensing the motion of an object across the manipulating finger(s) is critical for robust dexterous manipulation [16]. In order to evaluate the performance of the HTA's ability to detect motion over the surface of the robotic finger, a blind-fold experiment was set up, and completed by 8 participants (7 male adults, 1 female adult), with each participant wearing the HTA and benchmark heavy work glove in turn. The participants were asked to turn a dial with their unencumbered hand, with the aim of matching the perceived direction of motion of an object as seen in Fig. 8. In order to nullify the effects of learning, participants were given the glove or the HTA in a random order. Each taxel/location was depressed 5 times in a randomised order, totalling 35 depressions per participant per trial.

4 Results & Discussion

4.1 Hydraulic Tactile Array Benchmarking

4.1.1 Positional Identification

The HTA improved fingertip positional information identification of users when compared to the baseline heavy work glove for all but one of the taxels (Fig. 9). A Mann-Whitney U test was performed to find whether the average accuracy was significantly improved for each taxel/position: A, E, and F had a p-value < 0.05, and that G's improvement had a p-value of < 0.01. This suggests that the direct contact of the silicone pads using the taxel array improves tactile sensitivity to direct pressure, especially around the lower fringes of the fingertip. Despite the low number of participants, the positive significance result for the taxels over the glove is promising for future applications of HTAs. Despite this, further experimentation is needed, due to the lack of explanation for the anomalously poor performance of the B taxel (10 o'clock) relative to the other taxels on the HTA, while a similar pattern is not observed in the glove's results. This may be explained by a manufacturing defect, or the positioning of the HTA on participants' fingers. The relationship between the

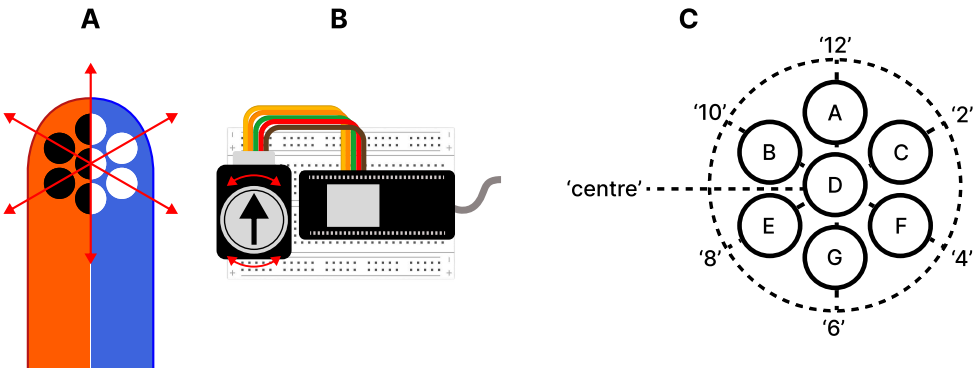

Figure 8 Illustrations of experiment methods. **A** represents the benchmark glove with markings and the HTA input. The red arrows denote the 6 directions in which the motion across the surface was applied during the motion direction experiments. **B** is a representation of the input device comprised of a dial and an STM-8266 based device used for the recording of the measured angle when the dial is depressed by the participant. **C** is the 'clock-face analogy' used to aid participants to report which location they felt pressure through the HTA or heavy work glove during the positional identification experiments. This enabled participants to visualise the input points in an easier way compared to the '$ABCDEFG$' format.

participants' finger-size and performance was investigated, as seen in Fig. 11. There is a positive correlation between finger size and performance on the positional accuracy tactility test with an R-squared of 0.67 for the HTA, and 0.34 for the glove. The equations for line of best fit for the HTA and glove results compared to participant finger size are:

$$y_h = 0.24x - 0.07, \ \& \ y_g = 0.29x - 0.45,$$

For the HTA, the gradient of its equation is shallower, suggesting that it may be less susceptible to tactile performance degradation with decreasing finger size (Fig. 11). However, without further investigation with a larger sample size, it is difficult to determine whether the difference between the two gradients is significant.

4.1.2 Motion Direction Identification

For the 8 participants who completed both the HTA and benchmark glove direction tests, the results showed that the mean absolute angular error between the perceived and real direction was decreased with the HTA but with low statistical significance per the Mann-Whitney U test, with significance levels for the 6 directions ranging between $p = 0.0849$ for 0°and $p = 0.9292$ for 120° . The significance of the improvement in the average performance among all directions as a single value is $p = 0.3095$.

The decreased significance of the performance improvement in the motion and direction test when compared to the positional stimuli test may be explained by the direction of strain in the fingertip, due to the anisotropic orientation and distribution of mechanoreceptors [3]. Interestingly, both the HTA and benchmark glove results exhibited anisotropic results, with the 300° direction being least accurate for both (Fig. 12). This could be due to the variance of sensitivity of the outer and inner edges of the index finger. This claim is supported by the asymmetrical mapping of mechanoreceptors on the finger-tip shown in Birznieks 2001 [3], but this hypothesis will need further testing to be validated.

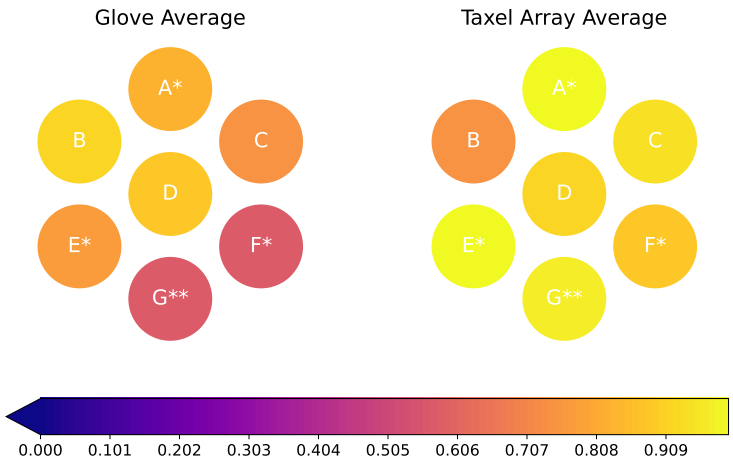

Figure 9 The average accuracy of identification of applied pressure for each location for the glove (left), and the taxel array (right). Statistical significance of the difference between the performance of the glove and taxel is calculated using a Mann-Whitney U test is shown as $* = p < 0.05$ and $** = p < 0.01$ level.

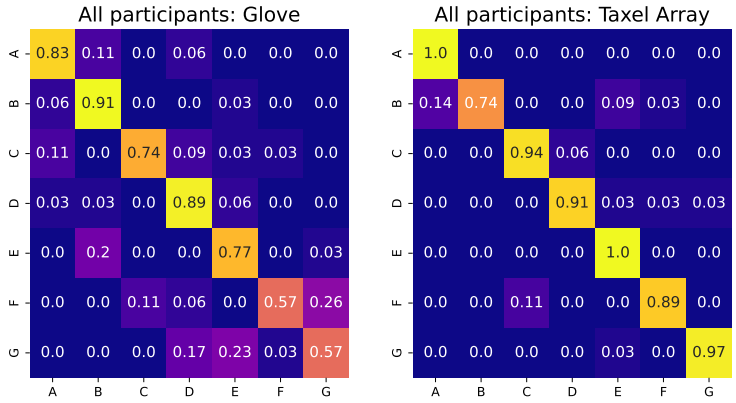

Figure 10 The confusion matrices showing the relationship between actual positional input vs perceived positional input for both the glove and the taxel array.

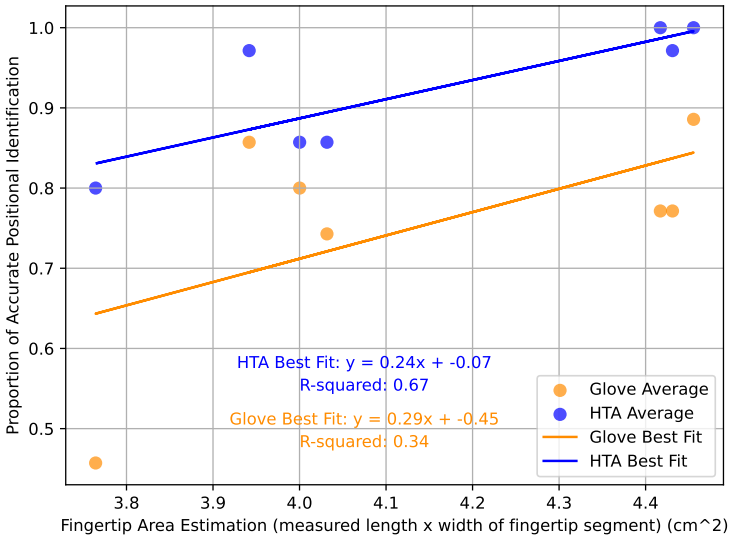

Figure 11 The relationship between a participant's finger area (calculated from measured finger segment length multiplied by the width), and their performance at the positional accuracy tactility test. There is a positive correlation between finger size and performance for both the HTA and glove.

4.2 Fabrication & Performance Discussion

The fabrication of the PAST device encountered several challenges, primarily related to sealing and bubble mitigation in both the Hydraulic Linkage (HL) and Hydraulically Actuated (HTA) subsystems. In the HL subsystem, the repeated use of proprietary syringes and Luer locks, originally designed for single-use, led to a degradation in their performance. While the choice of materials for the PAST device was suitable for proof-of-concept purposes, incorporating higher quality hydraulic cylinders would enhance the performance and longevity of future prototypes. The PVC tubing used for the transmission lines of the HL subsystem also introduced transparency issues due to diameter expansion under applied pressure. The effect of this in short tubes is minimal, but with additional length, the effect becomes substantial. This damping effect can be further exacerbated by the presence of air bubbles in the system, due to seal failure around the Luer locks and the syringe plunger. The effects of air in the lines is particularly noticeable when applying negative pressure through a transmission line with bubbles. This causes expansion of the air pockets, increasing the volume in the line, and if failing to overcome static friction, inhibiting movement of the end-effector. A possible solution to this issue is the bilateral pressurisation of hydraulic transmission lines by spring-loading both sides. However, this may not be necessary with the use of higher quality materials and seals, or with the implementation of a double-line approach, which ensures positive pressure in one of the lines in either direction, as is discussed in Whitney et al. as a comparison to their actuator [21].

Overall, overcoming challenges related to sealing and bubble mitigation is crucial to improving the fabrication and performance of the PAST device. The use of higher quality materials, improved seals, and the consideration of alternative pressurisation approaches can enhance the functionality and longevity of future prototypes.

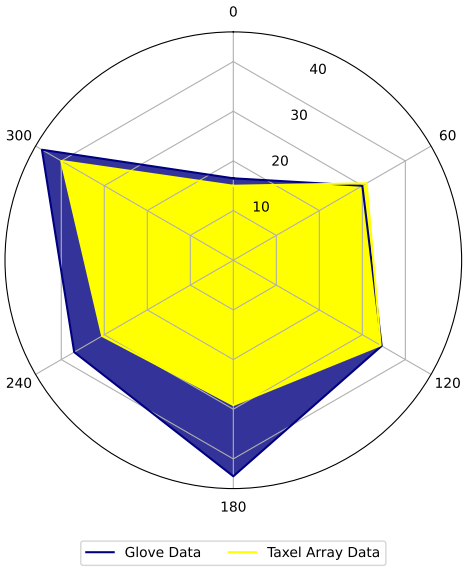

Figure 12 Mean absolute angular error of the participants using the heavy work glove and the taxel array (N=8) in the 6 motion input direction (0, 60, 120, 180, 240, and 300). The HTA results outperform the benchmark glove results, further investigation is needed to determine significance.

5 Conclusions

The PAST device has successfully demonstrated an alternative method for improving tactile sensitivity without compromising protection, offering a promising approach to enhance the dexterity of astronauts during EVA. However, further work is necessary to fully develop the PAST device paradigm for practical use.

5.1 Further Design Iterations

Improving the fidelity of prototypes by using higher-quality materials, actuators, and more complex HL designs, as well as integrating the PAST device with a pressurised protective suit, will bring PAST technology closer to the level required for practical applications.

Utilising a rolling seal for the HL cylinders such as is used in Whitney et. al. [21] and Lam et. al. [6] would not only increase the transparency of the mechanism but would also decrease static and *breakloose* friction by eliminating dry-contact area in the cylinders [8].

The main constraint of the PAST device's utility is the design of the robotic hand. The two 2DoF fingered design cannot perform important actions that the human hand is capable of, such as prehensile grips, form-clasping, and caging. To address some of these issues, the design can be updated in a number of ways:

- An alternative linkage design can be developed for the HL, which may enable form-clasping, such as the 2DoF per finger design used by the thumb and index of the Festo ExoHand to both track and actuate motion [5].
- The addition of more fingers to the HL would enable complex in-hand manipulation, such as in the RUTH hand [9].
- The addition of additional transferable degrees of freedom from the human-side to the robot-side of the HL. This would enable more natural and complex movements to be transmitted, increasing anthropomorphism.

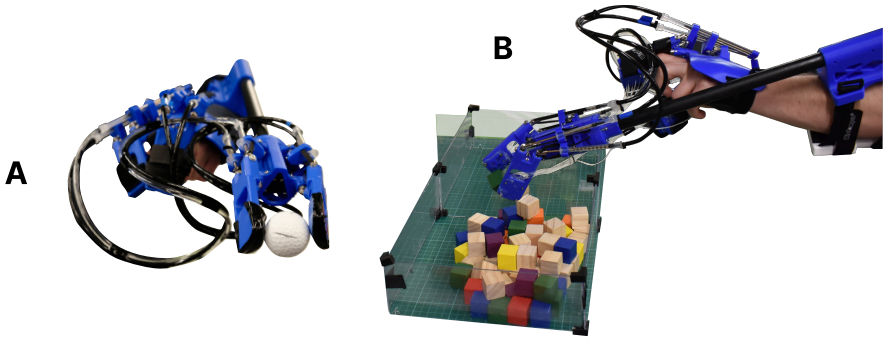

Figure 13 **A** shows the HL without the HTA picking up and manipulating a golf ball. **B** shows a block manipulation demonstration task being carried out with the HL and HTA subsystems combined.

The PAST device successfully transfers tactility, but with an extended limb, a perception of *embodiment* can be expected with the robotic hand [4]. However, further work must be done to validate embodiment.

5.2 Alternative applications

Beyond use for improving dexterity in space, PAST devices have further applications in environments and situations which favour a layer of separation between the operator and the task, while relying on local communication. These applications could include use by deep-sea divers, HazMat handlers, and even actors wearing decorative exo-suits as an attraction at theme-parks. The principles of PAST could also be applied in the precise control of machinery or tools, such as emergency surgery with surgical robots that require no external power.

5.3 Final Comment

In conclusion, the PAST approach shows promise in enhancing astronaut dexterity during EVA as well as other potential applications. Preliminary data indicates significant improvement in positional tactile sensitivity and some improvement in directional tactile sensitivity when compared to HWGs. However, further investigation is needed for comparison with high-fidelity pressurised EVA gloves. The tactility experiments have also revealed insights into the varying sensitivity of the fingertip, prompting further research questions in this area. Initial grasp and manipulation abilities have been demonstrated, but further experimentation is required to fully characterise the prototype. Overall, the preliminary tests provide a clear direction for further iteration and development of passively actuated short-range telehaptic devices.

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Mixed-Initiative Dynamic Autonomy Through Variable Levels of Immersion and Control (MIDA-VIC): A New Paradigm for Collaborative Robotic Teleoperation in Space Exploration

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Abstract

In this position paper, we propose the new control paradigm and conceptual framework MIDA-VIC for collaborative robotic teleoperation in space exploration and beyond. Such teleoperation is a complex and demanding team effort with distributed responsibilities that require both efficient human-robot and human-human collaboration. To address these challenges, we propose a new paradigm of mixed-initiative dynamic autonomy for robotic teleoperation. It exploits recent advances in human-computer interaction (HCI), human-robot interaction (HRI), augmented and virtual reality (AR/VR), and artificial intelligence (AI) research. By integrating methods from multiple fields, our paradigm allows human operators to choose their preferred level of immersion, from traditional 2D graphical user interfaces (GUIs) to fully immersive AR/VR environments. It also supports a dynamic adjustment of the level of control, ranging from direct motor commands (e.g., using a joystick) to high-level task delegation using AI (e.g., instructing the robot via natural language to select a path or explore autonomously). In addition, we propose a mixed-initiative paradigm in which a robot can also take the initiative, request human assistance, and propose the specific level of immersion and control to the human operator that it currently considers useful for effective and efficient collaboration.

2012 ACM Subject Classification Human-centered computing → Mixed / augmented reality; Human-centered computing → Collaborative interaction; Human-centered computing → Natural language interfaces

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1 Introduction

The teleoperation of a complex robotic system is a demanding team activity. This is especially true for a space telerobot, which is a remotely operated robot that performs work in a rich space environment that could include the unstructured surface of a planet or asteroid, or complex operational settings such as on-orbit servicing of a satellite [13]. Human operators in a command center for space telerobots must deal with multiple challenges such as long communication delays, incomplete and uncertain information from sensors or cameras, and changing requirements for the level of control, ranging from low-level direct control of motors and nonautonomous functions to high-level supervisory control of (semi)autonomous processes. Missions involving Lunar or Mars rovers require multiple operators to manage and


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supervise these partially autonomous systems, ensuring that operational goals are met while maintaining the health of the rover and its science payloads [16]. Typically, human operators assume various specialized roles to ensure the successful teleoperation of robotic rovers. The following real-world examples, which were simplified for the purpose of this paper, illustrate the typical complexity and breadth of involved roles:

- *Command and Control Operators:* These individuals are responsible for sending movement commands to the rover, such as navigation paths and manipulator operations. They utilize real-time data and pre-planned sequences to guide the rover's actions. For example, command operators ensure that the rover safely follows planned traverses and maneuvers within time and power constraints.
- *System Health Monitors:* Dedicated engineers continuously observe the rover's telemetry and subsystem status to maintain its health. They track critical metrics including power levels, temperatures, communication signal strength, and motor currents. For instance, mission teams often assign specialists to monitor system or payload health (battery, instruments, etc.) and flag any issues.
- *Science Team Members:* These experts analyze data collected by the rover's instruments, such as imagery and spectroscopic readings, to make scientific interpretations and decisions about future exploration targets.
- *Communication Specialists:* Given the significant communication delays in space missions, these operators manage the scheduling and transmission of data between the rover and Earth, ensuring synchronization and data integrity.

To address these multiple challenges and roles in space human-robot interaction, this position paper proposes the new MIDA-VIC conceptual framework for **m**ixed-**i**nitiative **d**ynamic **a**utonomy through **v**ariable levels of **i**mmersion and **c**ontrol. We explain the different components of the proposed framework and illustrate how it can be used to envision future control systems for space telerobots. By this, we lay the foundation for future research on MIDA-VIC to build prototypes of future collaborative systems for robotic teleoperation and to collect empirical data about their benefits from user studies.

2 Background and Related Work

The MIDA-VIC control paradigm is based on three key concepts that we elaborate in the following: (1) *situation awareness* as an overall design goal for collaborative control systems, (2) *variable levels of immersion* for human-robot interfaces, and (3) *variable level of control* that human controllers exert over an non-/semi- or fully autonomous telerobot.

2.1 Situation Awareness

Given the complex and collaborative nature of robotic teleoperation in space exploration, research in human factors (HF), human-computer interaction (HCI), and human-robot interaction (HRI) has aimed to reduce the mental, physical, and temporal demands of teleoperation. For example, innovative designs of user interfaces, visualizations, interaction techniques, and control room layouts are intended to leave teams with more mental, physical, and temporal resources to develop a good collective *situation awareness* (SA).

SA is commonly defined after Mica R. Endsley as "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [8]. In other words, SA is a person's real-time understanding of "what is going on" around them and what might happen next. Endsley's model breaks SA into three levels that can be applied to our telerobotic scenario:

- Level 1: *Perception* – Being aware of the relevant cues in the environment. For a rover operator, this means perceiving key data from the robot and its surroundings: e.g. receiving camera images, seeing obstacle locations, reading the rover's speed, battery level, or telemetry warnings. Without perceiving these status elements, an operator cannot move to higher awareness.
- Level 2: *Comprehension* – Understanding what those perceived elements mean in context. In teleoperation, the operator must interpret the sensor data correctly – for instance, recognizing that "the rover's wheel slip is high", which could indicate that the terrain is soft sand. Alternatively, a certain rock in the camera view might be a science target of interest. Comprehension implies that the operator synthesizes different data points into a holistic picture ("the rover is tilted on a slope and losing traction"). This level of awareness allows the human to assess the significance of the current situation relative to mission goals.
- Level 3: *Projection* – Anticipating the future status of elements in the environment. In the rover scenario, this is the ability to predict what will happen next: if the rover continues on its path, will it get stuck? If the battery is at 20% now, will it last through the next planned drive? Good SA means that the operator can project ahead a few minutes or hours based on the current trends. This foresight is critical for decision-making, such as planning maneuvers to avoid an obstacle or scheduling a return to base before sunset.

Endsley's framework is highly relevant in this context because teleoperators operate in dynamic environments (another planet's surface) where they must continuously perceive changes, understand their implications, and predict the outcomes to make correct decisions. However, achieving robust SA in a teleoperation setting is challenging. The operator is separated from the rover by distance and relies on information constrained by limited bandwidth, which can degrade awareness. Endsley and others point out several factors that can undermine situation awareness for remote operators: poor sensory information, communication delays, and interface complexity are all obstacles to building a clear picture [9].

2.2 Variable Levels of Immersion

Virtual Reality (VR) for robotic teleoperation in space has been proposed since the 1990s [5] and potentially improves SA by providing more sensory information and reducing interface complexity. However, isolating operators in VR from their real-world team members and command center can also undermine SA and efficient collaboration. In our own previous work on collaborative *Transitional Interfaces* [25] and using Augmented Reality (AR) for HRI [3], we have examined different strategies for immersive technologies that could support operators without such disadvantages.

For example, our research on Transitional Interfaces explores how 2D graphical user interfaces (GUIs) can be seamlessly integrated with AR and VR to support teams. We have examined new ways for human collaborators to use variable levels of immersion, i.e., seamlessly switching between (1) personal, immersive, and stereoscopic views with good depth perception in VR during spatial tasks, (2) less immersive, yet stereoscopic, 3D displays of spatial information in AR that do not isolate operators from their co-located human team members in the real world, or (3) "flat" 2D maps and charts on shared vertical or horizontal displays for efficient overview and group discussion. By this, we intend to better support teams during phases of tightly-coupled collaboration as well as more loosely-coupled parallel work and increase overall *workspace awareness* [25]. As we discuss in [24], technologies using variable levels of immersion could also help operators to better deal with communication latencies and asynchronous collaboration over long distances in space.

In HRI, we have explored approaches to increase SA by providing the operator with contextual visual information that augments the robot in such teleoperation scenarios. In particular, we were able to show how such visual augmentations can improve the user's ability to perceive and comprehend the robot's position with respect to its surroundings and potential target objects [3]. We also found a clear trade-off regarding visual complexity that needs to be taken into account when designing such augmentation [4]. Regarding the third level of SA – Projection, a literature review on understanding robot intent has shown that it is imminent to communicate not only motion but also current state or guide the user's attention [21]. It also showed that the level of immersion can vary quite a bit between different communication strategies, ranging from direct LED feedback on-robot joints [26] to visual path predictions in AR/VR [27], which all come with certain advantages and drawbacks, highlighting the need for variable levels of immersion. Regarding the question of how to realize such variable levels of immersion, we developed the AdaptiX framework, which provides a technical architecture that allows HRI to be designed along the full Mixed-Reality Continuum [20].

2.3 Variable Levels of Control

Good situation awareness, including projection and anticipation of future states of the environment as well as the individual actors, is vital for the teleoperation of robots due to the roundtrip communication delays of radio signals. These communication latencies are typically a few hundred milliseconds in low Earth orbit (LEO), but can reach between 5 to 14 seconds in Earth-Lunar or up to 40 minutes in Earth-Mars communication [19].

As latencies increase, control paradigms have to change as well. Manual control (or direct teleoperation), involving the complete control of the actuators on the robot by the operator, must be increasingly enhanced with supervisory control, in which the operator sends intermittent commands to a (semi-)autonomous robot and intervenes only when necessary. Manual and supervisory control may be utilized by the same telerobot, as evidenced by the popular Mars Curiosity Rover [15]. Due to the high latency of Mars communication, operators of Curiosity could choose between three layers of control to drive the rover [18], applying a concept also known as traded control [12]:

1. Low-level motor control commands that specify exactly how much to rotate each drive wheel and turn each steering wheel actuator.
2. Directed driving primitives for driving along circular arcs (of which straight-line driving and turn-in-place are special cases).
3. Autonomous path selection for reaching a goal while reacting to unexpected changes along the way.

Another perspective on these different layers is to look at the type of tasks the user takes on in such situations, i.e. rather on a strategic level (3) or more towards tactical (2) or operational (1) involvement. In particular, on the tactical and operational level, the possibility of shared control arises [11]. Such approaches aim to combine human input with robot operations without a clear traded control scheme, i.e., both operator and human act or respond, and the overall resulting action is a combination or fusion of these different inputs.

Approaches from previous research and literature show that this can often be used to optimize human input through the use of machine learning and deep neural networks, e.g. CNNs [10, 22, 6, 23]. This shift necessitates the development of advanced human-robot autonomy frameworks [12, 1] but also mixed-initiative control strategies to maintain effective operation despite communication delays.

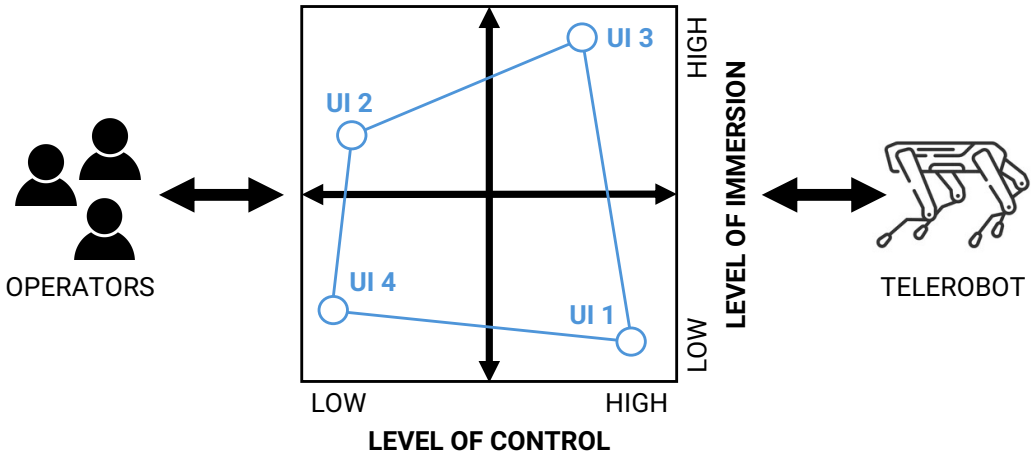

Figure 1 An illustration of the MIDA-VIC control paradigm. Co-located human operators in the control room are shown on the left and the telerobot for remote operation is on the right. Operators and telerobot communicate and collaborate via a set of connected user interfaces which are used in parallel inside the control room, e.g., UIs 1-4 (center). By switching between or adapting UIs, the human operators can dynamically adjust the current level of their control over the robot (horizontal axis) and the level of immersion (vertical axis) for each UI. By this, they can ensure that the robot's degree of autonomy, the visual representation of sensor data on the UI, input/output modalities for control, and UI complexity best meet the current task at hand and its situational needs.

A possible direction in the context of variable control paradigms is the integration of Large Language Models (LLMs) to use natural language as a primary interface for human-robot communication [7, 2, 17]. With their ability to understand and generate context-aware dialogue, LLMs enable robots to be collaborative agents that are capable of participating in mission workflows as embodied conversational team members. Equipped with an LLM, a robot can report its internal state, explain its behavior, and reason about its environment using natural language. This enables a more natural interaction where operators can describe high-level goals or ask situational questions (e.g., "Are there any promising rock formations nearby?"), and the robot can respond accordingly (e.g., "I detected two interesting objects 15 meters northwest. Would you like me to investigate them?"). Such capabilities transform the robot into an active collaborator that can proactively provide suggestions, communicate uncertainties, or propose alternative aspects of the mixed-initiative paradigm that we propose. Future research should explore how LLMs can serve not only as conversational interfaces but also as reasoning layers for agent-like behavior in robotic systems. This includes dynamically adjusting language to support the operator's requirements, reasoning about high-level goals and constraints, and engaging in the negotiation of roles between humans and robots in long-term missions.

3 The MIDA-VIC Control Paradigm

Based on such previous work in HCI, HRI, AR/VR, and AI, we envision a new control paradigm for collaborative robotic teleoperation in space exploration and beyond. We refer to this paradigm as **m**ixed-**i**nitiative **d**ynamic **a**utonomy through **v**ariable levels of **i**mmersion and **c**ontrol (MIDA-VIC). The main components of MIDA-VIC are illustrated in Fig. 1.

MIDA-VIC enables multiple human operators to freely choose their individual *level of immersion*, ranging from conventional mouse- and keyboard-operated 2D graphical user interfaces to immersive, stereoscopic 3D visualizations in AR/VR with 3D input devices. It also allows them to dynamically adjust their *level of control*, ranging from low-level motor control commands, for example, with a joystick, to delegating high-level tasks such as autonomous path selection or autonomous exploration of an area to the robot, e.g., by conversing with the robot about its tasks, its status, and its progress in natural language. In consequence, the two-dimensional position between low and high levels of control (Fig. 1 horizontal axis) and low and high levels of immersion (Fig. 1 vertical axis) define the interaction style of how a operator and the telerobot temporarily communicate, interact, and collaborate. Multiple interaction styles can co-exist, so that operators 1-3 can each use their preferred interaction style(s) for collaborative teleoperation. They can always adjust their individual level of control and immersion to align it with their current role, responsibility, and goals. In addition, MIDA-VIC is a mixed-initiative paradigm [14] in which a robot can also take the initiative, request human assistance, and propose the specific level of immersion and control to the human operator that it currently considers useful for effective and efficient collaboration.

Example UI 1. A command and control operator could use the rather traditional UI 1 with low immersion and a high level of control (see Fig. 1) to manually adjust each joint or motor of a robot or to reset subsystems. UI 1's I/O devices, visualizations and interaction techniques are optimized for highly precise and direct interactions with a robot using a traditional mouse- and keyboard-operated control panel on a desktop screen with a 2D GUI containing sensor readings, logs, consoles, sliders, and input fields to enable high-precision adjustments and for identifying or addressing root causes of problems. UI 1 is the operators' obvious choice whenever they need to intervene in case of a failure of a high-level autonomous function or when the robot encounters an unexpected situation and asks for human assistance. It provides full and precise control but increases operators' mental and temporal demands.

Example UI 2. UI 2 is a high-immersion and low-level-of-control UI (see Fig. 1) that could be used by a science team member to supervise an automated 3D mapping process of the robot's environment and surrounding surface. This 3D reconstruction is generated through a highly automated process by continuously transmitting 360° camera images and laser distance measurements to the command center where the data is recorded, processed, and collated into a 3D reconstruction of the environment. For supervision of the process, the resulting map data is visualized as a steadily growing and increasingly detailed 3D map on an interactive multi-touch tabletop that enables operators to use gestures for moving, panning, and zooming their virtual camera to inspect data quality. Such a non-stereoscopic projection of automatically collected 3D data on a "flat" screen could be further enhanced by enabling operators to additionally wear an AR/VR head-mounted display (HMD), so that terrain data could additionally appear as stereoscopic AR "holograms" above or next to the tabletop. In some cases, operators could also decide to fully immerse themselves in a stereoscopic 3D VR visualization to "fly" through the data. Using AR/VR in this manner would move UI 2 further towards the top in Fig. 1.

Example UI 3. UI 3 with a high level of control and immersion becomes relevant when the robot's operation requires manual control of a mechanical subsystem, e.g., of a robotic arm in a challenging environment. For example, this could be picking up a geological sample from

the ground while other rocks or rock formations are in close proximity and might also cover parts of a camera image. To help operators navigate the arm within a space that might also contain obstacles or is partially occluded, the UI ideally provides a stereoscopic display of a precise 3D reconstruction with good depth perception that can be used to plan, preview, and execute arm movements. Here, immersion is not only a question of visual output but also includes the possibility for physical and spatial input, e.g., by tracking human arm, hand, or controller movements in space.

Example UI 4. UI 4 uses voice I/O with natural language to enable hands-free and eyes-free human-robot control and communication. Thanks to rapid advances in AI, including natural language processing and reasoning with LLMs, this interaction style could become a powerful tool for efficient human-robot communication, despite its low level of control and immersion. For example, operators could verbally describe a desired target location or movement pattern to the robot as they would describe it to another human team member. This could also include instructions or informal "programming" of the robot to enable the robot to autonomously react to future events or changes in the environment, especially when human operators would be too slow to react due to communication delays. Using LLMs, UI 4 could also add a layer of high-level "natural" human-robot communication, during which the robot embodies an agent or team member. For example, the robot could provide status updates and reports in natural language that adapt to the situational needs and mental load of the human operators, e.g., in the amount of information, level of detail, and linguistic style. It will also be interesting to explore to what extent LLMs will enable agents to reason about the state of the robot and its environment in relation to its goals and will be able to come up with proposals for improving mission efficiency or solving critical challenges.

It is noteworthy, that UI 1-4 are just initial examples that we have developed to start further design explorations and that many other helpful configurations of input/output devices, modalities, and levels of control and immersion could become a part of future robotic teleoperation. Also, at the heart of the MIDA-VIC paradigm is the perspective that these styles will co-exist and will need to be used in parallel in order to address the complexity of robotic teleoperation in space.

4 Implications for Future Research

While there is a growing body of knowledge on successful and effective shared and traded control approaches, little is known about how different user interaction designs affect them. For example, previous research found that even very small changes at the presentation level of robot motion intent led to different perceptions of robot autonomy and potential for overtrust [22]. Adding to this, while there are numerous ways to communicate between robot and human, both to express intent or to control, there is a lack of systematic analysis and comparison. For example, research on robot intent identified a clear research gap in terms of theory building and design principles based on empirical data to better understand the benefits and drawbacks of certain approaches in comparison to each other [21].

Using Transitional Interfaces [25] for providing variable levels of immersion could offer a path to overcome this by providing a context- and situation-dependent interaction paradigm. Furthermore, this integration could reduce challenges in collaborative SA acquisition through operator-centric presentation of information tailored to different levels of immersion and control, even in asynchronous teleoperations [24]. However, previous work has found that establishing group and workspace awareness among a team that simultaneously uses different

levels of immersion and different display technologies is not trivial [25]. In some cases, teams tried to strictly avoid different immersion levels, resulting in inferior task performance. Future research in HCI and AR/VR will need to identify typical barriers to more efficient use of variable levels of immersion and overcome them using innovative designs.

Finally, our vision of delegating formerly human tasks to autonomous systems or conversing with a robotic system in natural language raises important questions, not only about technological feasibility but also psychological effects. Adverse effects of increased automation could include overtrust [22] and generally weaker supervision of systems. Also, human operators of telerobotic systems in space exploration are highly trained, skilled, and experienced professionals. Therefore, "natural" communication with a robot that reduces human task load but also human control could interfere with a team's basic psychological needs such as competence, i.e., the experience of effectiveness and mastery, and autonomy, i.e., the experience of volition and willingness, as was examined in previous work on supporting experienced seafarers with decision support systems for energy-efficient navigation [28].

5 Conclusion

We have introduced MIDA-VIC, a novel control paradigm for collaborative robotic teleoperation in space exploration. MIDA-VIC aims to address mixed-initiative dynamic autonomy settings with variable levels of immersion and control. By leveraging advances in HCI, HRI, AR/VR, and AI, MIDA-VIC enables human operators and robotic systems to flexibly adapt their collaboration modes to the requirements of specific tasks and operational constraints. Our conceptual framework allows for seamless transitions between immersive and non-immersive interfaces, as well as between manual, shared, and autonomous control. The goal is to enable mission teams to operate more effectively across varying task phases and technical challenges. MIDA-VIC supports diverse roles within teleoperation teams, considers the requirements and constraints of autonomous agents, and addresses the necessity of user- and robot-driven initiative. By supporting multiple interaction approaches in parallel and by enabling dynamic adjustments in both immersion and control, MIDA-VIC aims to provide the conceptual foundation for more responsive and intuitive teleoperation systems. We anticipate that the introduced paradigm has the potential to have broad implications not only for space exploration but also for other domains of remote robotic operation where human-robot collaboration is essential under complex and uncertain conditions. Future research should further investigate the design space of interaction modalities, the cognitive and operational impact of dynamic control, and the potential of LLMs and AI agents in enabling more natural human-robot interactions. MIDA-VIC offers a framework for exploring these directions to guide the development of next-generation collaborative systems.

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(Can't) Fly Me to the Moon or Mars? Context of Use Analysis Approaches for Space Exploration

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Abstract

Contexts of use are a central concept of research and development in human-computer interaction (HCI). Their in-depth understanding is a key for usable and acceptable computer-aided solutions and a particular challenge in connection with space exploration. It is necessary to examine which of the established approaches can be implemented here and where methodological adjustments are necessary. This article provides a systematic consideration of three perspectives to understand space contexts of use: theory and literature, imparted experiential knowledge, and personal experience. Potentials and risks are evaluated. The findings of HCI research in safety-critical contexts and under COVID-19 conditions that can be transferred to space HCI are taken up.

2012 ACM Subject Classification Human-centered computing → HCI design and evaluation methods

Keywords and phrases Context of Use, Experiential Knowledge, Remote Contextual Inquiry

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1 Introduction

The concept of contexts of use in the sense of "combination[s] of users, goals and tasks, resources, and [technical, physical, social, cultural and organizational] environment" [13] is central to research and development in the field of human computer interaction (HCI). Their in-depth understanding is the key to developing usable solutions and enabling positive user experiences. Their lack of understanding is one of the main reasons for usage and acceptance problems.

With regard to space exploration and missions, several challenges have to be mastered in order to gain a sufficient context of use understanding:

- Access to certain technical and physical environments is limited (e.g., control rooms) or hardly possible at all (e.g., space shuttles, space stations, other planets).
- The number of potential users and suitable experts is comparatively low compared to other contexts of use. Due to their demanding professional activities, they cannot easily be recruited to participate in human-centered design processes.
- Cultural and organizational environments are complex and are characterized by a large number of regulatory rules that require a great deal of familiarization for people from outside.

In addition, certain usage situations and user requirements are difficult to analyze in advance, despite all the planning and preparation, especially in borderline areas of personal experience (e.g. long-term isolation [26]).

However, in order to do justice to the "exciting opportunity for researchers in HCI to contribute to the great endeavor of space exploration" [27], understanding the respective usage contexts is one, if not the first step. In the following, related work is discussed before 3 possible perspectives on the context of use are presented. We end with the conclusion that "fly me to the Moon or Mars" should become a reality for HCI researchers, provided that space exploration no longer remains an experience for a very small number of people.

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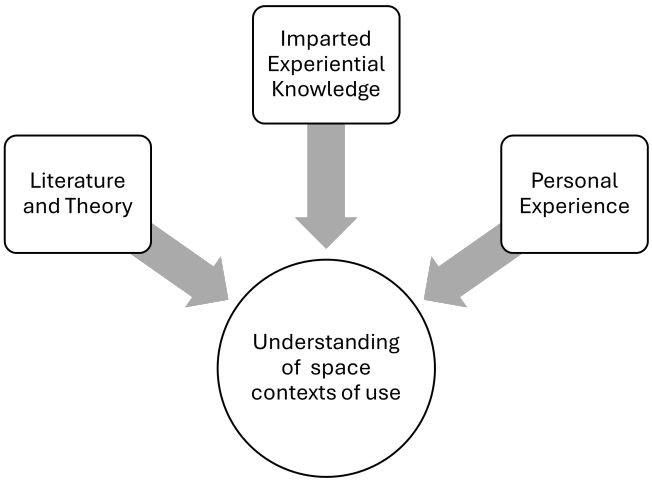

Figure 1 Different Approaches to Space Contexts of Use Understanding.

2 Background and Related Work

Previous research has already addressed questions whether earth-based interaction design frameworks are applicable to extraterrestrial environments [31] or how to bridge the gap between participatory design and space engineering [23]. One of the findings is: "The very notion of context of use [...] may need revisiting for new relevant dimensions in the interplanetary perspective." While they discuss human-centered and participatory design frameworks as well as suitable evaluation environments (e.g. size, lighting conditions, gravity), specific recommendations for space-related context of use analysis have been given occasionally (e.g., [5]).

Extending the consideration, specific challenges of studying "extreme environments" [22] as well as context of use characteristics [1] in general have already been highlighted. For example, special requirements were identified to define the contexts of use of mobile devices [17]. However, the transferability of these findings and recommendations to HCI in space has not been discussed sufficiently.

3 Three Perspectives on Space Contexts of Use

In the following, the three basic approaches to understanding usage contexts shown in Figure 1 are considered in connection with space missions and space exploration. They are not specific to space HCI, but are rather evident in a large number of (security-relevant) HCI research projects [21]. The respective characteristics and procedures in different domains are therefore more important.

These approaches reflect Herczeg's structure for evaluation approaches of interactive systems (theory-based, task-based, user-based evaluation) [10]. Since, in the sense of an iterative human-centered development approach [14], the evaluation of a previous stage of development can also motivate an extended/new analysis of a context of use, among other things, this analysis-evaluation-connection does not seem coincidental.

3.1 Literature and Theory

Apart from proceedings of space- and HCI-specific workshops and conferences [27, 28], space agencies (ESA[1], NASA[2]) and other expert societies (e.g., German Society for Aeronautics and Astronautics[3]) provide HCI researchers with access to various technical reports, standards and playbook considerations. This rich body of knowledge allows for a deep exploration of key terms and concepts that HCI researchers need to understand.

However, challenges are to find the needle in the haystack and to ensure a proper understanding of the content provided. In principle, both challenges also occur in other safety-critical contexts, but the necessary complexity of technical solutions for space operations and the diverse areas of standardization, see [18] on the topic of sustainability in space operations alone, are then even more special. In order to understand space research, it may also be necessary to have sufficient knowledge of domains with which HCI experts may have had little experience in their training (astrophysics, aerospace engineering).

3.2 Imparted Experiential Knowledge

Numerous studies involving former and prospective astronauts [6], their families [15], control room staff [2], and other experts [19] show that it is possible to draw on experiential knowledge in the space domain.

As in other safety-critical and expert-driven working domains, access and availability to these special and numerically rather small target groups are critical. Qualitative and often temporally synchronous approaches (interviews, field studies) should be combined with quantitative and temporally asynchronous measures (e.g., questionnaires) which allow for certain response periods and respond rates [9]. In addition, consideration should be given to whether corresponding feedback and work results should be made available in the sense of open educational (research) resources in order to avoid multiple surveys of the same issues.

In connection with the previous statements, the level of familiarization with the specific space-related context of use must, of course, be taken into account in order to gather relevant findings and not waste the experts' limited resources unnecessarily.

3.3 Personal Experience

Personal experience can first of all be divided into two types:

- direct (and also physical) involvement in the context of use, be it in control rooms, simulators, or as a crew member;
- indirect participatory observation, e.g. in the form of video transmissions from spaceships or space stations.

Visiting space control centers and simulators is already possible today, with the appropriate amount of preparation [2]. However, the number of advanced simulators is limited and involves corresponding travel and organization costs. Especially in early project stages and for low-fidelity prototyping approaches, decentralized and flexible solutions would be desirable. Promising mixed reality approaches should be pursued, e.g. with respect to gravity alterations on users [24] and environments [32]. Virtual reality has been considered to investigate the "effect of communication delay across interplanetary distances" [30] and

[1] https://www.esa.int/About_Us/Business_with_ESA/Space_Related_Standards2
[2] https://ntrs.nasa.gov/
[3] https://www.dglr.de/informieren/publikationen/

for space operations training [25]. Insights that can be expected from such approaches can certainly also make it easier to understand the respective contexts of use. Finally, space missions with participation of HCI researchers are still a topic that can be developed further. In order to avoid following an all-or-nothing approach, the role of usability engineering and user experience design approaches in space engineering should initially be examined in terms of maturity models like described by [4]. This could be followed by a gradual increase in importance in terms of decision-making powers, resources and culture.

Indirect observations are first of all a question of technical feasibility (bandwidth and latencies). In addition, appropriate equipment for users, e.g. with camera systems and sensor technology, as well as the physical environment (rooms, sections) is only ever conceivable with special consideration of safety and security requirements. Either existing infrastructure can be used or the potential dangers in terms of operating errors or security gaps must be carefully examined. Off-the-shelf hardware, as is often used in HCI studies, is generally not certified accordingly and is also integrated into infrastructures (communities, cloud systems) that hardly meet the specific requirements of space operations.

If the points mentioned above have been addressed, the question of the methodological approach arises. Many HCI analysis methods are based on the presence or even participation in the working environment (e.g., contextual inquiry [11], ethnography [16], field study [29]). Nevertheless, approaches have already been developed and tested that do not require direct presence or are related to the understanding of singular events in safety-critical environments that cannot be planned in advance. Remote contextual inquiry [8] or critical decision method (CDM) [20] are named here as examples. The former could take up the technical possibilities already available today for transmitting audio and video signals as well as sensor values over long distances and could therefore be carried out virtually live or with the help of a prepared script. With its retrospective approach, the latter can also be used after astronauts have returned from space missions, for example.

In connection with HCI research on distance, COVID-19 pandemic had (out of necessity) a huge impact with respect to participants, tools and study design [7, 3]. While face-to-face-experiments were prepared more carefully (e.g. social distancing, disinfection, checking body temperature), other approaches (remote, online, blended) were refined. Self-tracking and autoethnography [12] are just two methodological approaches that could also work well in space contexts. The experience gained and methodological adaptations that became necessary during and in the follow-up of this years can certainly be helpful to drive future HCI research in even more remote settings.

4 Conclusion

Understanding contexts of use, or even better, experiencing them first-hand, is not only an organizational and resource-intensive challenge in connection with space exploration. Both in safety-critical contexts and under specific framework conditions, e.g. during a pandemic, analysis approaches from general HCI research might fall short. This forces and enables us to think outside the box. Well-known approaches like remote contextual inquiry or critical decision method show that these challenges are not completely unique for space HCI. However, the special characteristics of the various space-related contexts of use (technical limitations, gravitational changes, long-term isolation) also require new methodological approaches in HCI research, possibly even a new understanding of the idea of context of use. Furthermore, a more specific approach to human-centered design in and for space in general is probably needed.

The previously discussed diversity of perspectives and methods should help to better understand even the most inaccessible contexts of use. However, the more space exploration becomes a "mass business", the greater the desire and demand from an HCI perspective: Fly me to the Moon or Mars. Beforehand, however, and in the sense of a research agenda guided by intermediate steps, it should be investigated how usability engineering and user experience design can achieve an increased level of maturity in connection with space operations in terms of degree and timing of involvement, resources, leadership and organizational culture.

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Understanding Time in Space: Improving Timeline Understandability for Uncrewed Space Systems

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Abstract

Timelines are critical in space exploration. Timelines facilitate planning, resource management, and automation of uncrewed missions. As NASA and other space agencies increasingly rely on timelines for autonomous spacecraft operations, ensuring their understandability and verifiability is essential for mission success. However, interdisciplinary design teams face challenges in interpreting timelines due to variations in cultural and educational backgrounds, leading to communication barriers and potential system mismatches. This work-in-progress research explores time-oriented data visualizations to improve timeline comprehension in space systems. We contribute (1) a survey of visualization techniques, identifying patterns and gaps in historic time-oriented data visualizations and industry tools, (2) a focus group pilot study analyzing user interpretations of timeline visualizations, and (3) a novel method for visualizing aggregate runs of a timeline on a complex system, including identification of key features for usability of aggregate-data visuals. Our findings inform future visualization strategies for debugging and verifying timelines in uncrewed systems. While focused on space, this research has broader implications for aerospace, robotics, and emergency response systems.

2012 ACM Subject Classification Human-centered computing → Empirical studies in visualization; Human-centered computing → Visualization theory, concepts and paradigms

Keywords and phrases Human-Ceneterd Design, Time-Oriented Data Visualization, Uncrewed Spacecraft Operations, Formal Methods

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1 Introduction

Timelines are used extensively in space exploration. On the International Space Station, timelines are used by ground controllers and crew members to manage schedules, meet deadlines, plan future operations, manage automated systems, and monitor and plan resource usage [7, 10, 30].

Timelines are also essential for managing automated space mission operations [6]. In the future, NASA will use timelines to manage long-term uncrewed operations of the Lunar Gateway by adding tasks and goals to the Vehicle System Manager timeline [17, 13]. These timelines must be understandable and verifiable for uncrewed spacecraft to operate safely and avoid catastrophic events.

Individuals in space system design teams develop their mental models of time through cultural influences [5] and formal education. However, design teams' inherently interdisciplinary nature introduces variations in educational backgrounds, which, alongside cultural


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Season	Aut	L-Aut	E-Win	Win	L-Win	E-Spr	Spr	L-Spr	E-Sum	Sum	L-Sum	E-Aut
Min Temp	-75	-85	-95	-110	-105	-95	-85	-75	-65	-50	-60	-70
Max Temp	-25	-35	-50	-65	-60	-45	-35	-25	5	15	10	-10

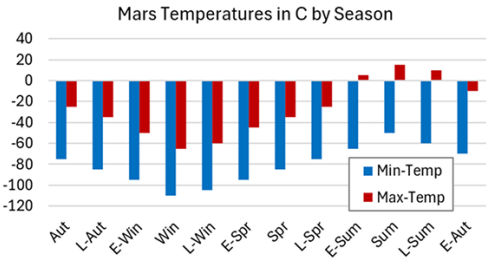

Figure 1 The data below shows hypothetical temperature data from the southern hemisphere of Mars throughout the Martian seasons. The visualizations show a heat map of the raw data, which makes patterns in increasing and decreasing temperatures more apparent, and the graph further shows the patterns and relationships of the two measurements over time.

differences, can lead to disparities in how team members perceive and interpret timelines [23, 22]. The disparities in understanding ultimately lead to ineffective communication and collaboration across design teams and could cause problems between system designs and users of the systems. Data visualization techniques enable patterns in data to be more easily recognized by humans, allowing a better understanding of data [8, 24] (see figure 1).

This work-in-progress paper presents ongoing research to enhance the understandability and usability of time-oriented data visualizations for space exploration, focusing on uncrewed space vehicles. This paper contributes 1) a short survey of time-oriented data visualizations, highlighting context-appropriate techniques for time-data visualization and pointing out areas for improvement in current visualization techniques used in industry tools (section 2). 2) An introduction to understanding a subset of users of timeline visualization techniques via a focus group pilot study, highlighting common trends in users' understanding of visualizations and why those understandings may appear as trends in other users in future studies. Additionally, the pilot study ideates future visualization directions and why those techniques may be effective visualization strategies (section 3.1). 3) A first look at a new technique for visualizing aggregates of time-oriented data used for visualizing failure locations of multiple runs of a complex system (section 3.2).

2 Preliminaries

The work presented in this paper is part of a broader effort to enhance the safety of safety-critical systems by improving the accessibility and usability of tools and techniques in formal methods. This section briefly introduces formal methods and overviews the resources used to review time-oriented data. This section ends with notable patterns from the review and opinions for implementing and improving the patterns.

2.1 Formal Methods

Safety-critical systems are those in which failures can lead to catastrophic harm, including severe injury, loss of human life, mission failure, environmental damage, property destruction, or significant financial loss. Safety-critical systems require rigorous verification to ensure their correctness and reliability. Traditional verification methods, such as unit testing, fault injection, and stress testing, find problems in a system, but they cannot show that your system is free from problems [3] (i.e., you can find the problems that you are checking for, but not the problems that you do not expect).

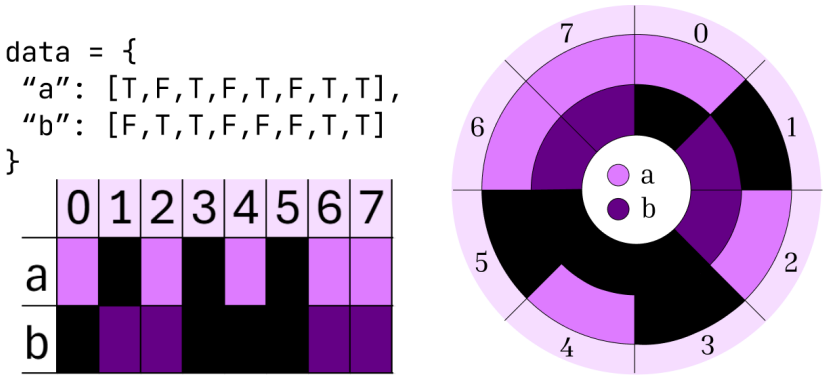

Figure 2 Two Boolean variables, representing the fault status of thermal control ("a") and power regulation subsystems ("b"), are visualized over 8 time steps in both linear and circular formats. Both representations show the same data, with black indicating False (a fault condition) and shades of purple indicating True (nominal operation). Key considerations for these representations include their scalability to larger variable sets and their interpretability in real-time mission operations.

Formal methods offer a more robust alternative by applying mathematical proofs and logic-based verification techniques to ensure that a system satisfies its specifications with provable soundness and completeness [33]. Formal methods are mandated by some government bodies in various certification procedures for uncrewed aircraft, supplementing traditional certification requirements for piloted aircraft [11].

Several formal methods and formal methods tools are designed to handle time-dependent systems, where timing constraints must be met for safe operation. For systems that rely on timelines, particularly in uncrewed space vehicles and other autonomous and semi-autonomous systems, such as underwater vehicles or search-and-rescue systems, timeline verification must ensure that conflicts do not arise that could lead to mission failure or catastrophic harm.

The specification of systems is one of the most critical and challenging aspects of the verification and validation of safety-critical systems [27]. Enhancing the understanding of effective visualization techniques can improve the creation and debugging of system specifications by providing human-friendly representations of otherwise highly technical and mathematical representations of system behaviors.

Runtime Verification

Runtime verification is a formal method for checking whether a system behaves as expected while running. Instead of analyzing the entire system simultaneously offline, Runtime Verification continuously monitors system executions against system requirements [28]. For example, in a satellite mission, a runtime monitor can track sensor data to detect anomalies, such as unexpected power drops. If a violation occurs, the monitor can trigger a response, such as switching to a backup power source, helping prevent mission failure in real-time [2].

2.2 Current Time-Oriented Data Visuals

The work presented in this preliminary survey on visualizing time-oriented data for space missions is based on the foundational research on visualizing time-oriented data by Aigner et al. [1] and an analysis of existing timeline visualization tools used in formal methods.

Historical Time-Data Visualizations

Aigner et al.'s work presents several types of data representations. We categorized them as linear, cyclical, and specialized. Linear time representations display data progressing in a single, continuous direction, which supports analysis of sequential events and long-term trends. In contrast, cyclical time representations emphasize patterns that repeat over consistent intervals (such as hours, days, or years) making them well-suited for identifying periodic behavior. Specialized data representations are those that do not follow linear or cyclical formats and are typically designed to support particular analytical needs or domains.

Systems engineering tends to adhere to a sequential representation of Boolean[1] data values, which can be visually represented as "on" or "off". Linear representations are suitable for this type of system execution because they align with the temporal progression of events, allow for straightforward visualization of state changes over time, and support familiar interactions such as scrolling, zooming, and variable comparison. Linear timelines can be extended by appending or inserting time steps. In contrast, circular representations would require increasing the radius to accommodate additional data and maintain readability, potentially increasing visual and implementation complexity. See figure 2 for an example of Boolean data represented linearly and cyclically.

Current Visualization Techniques Used in Industry and Research

FRET [12] is NASA's Formal Requirements Elicitation Tool. Fret turns the English language into formal requirements and displays Boolean values on a visual display similar to a guitar fretboard. The display is also similar to digital timing diagrams, where the line is up on a variable if it is True at that timestep and down if it is False. This potentially informs us that the users of FRET may be familiar with timing diagrams, which is an avenue to explore for visuals.

The Iowa State Applied Formal Methods class uses visuals to teach Linear Temporal Logic (LTL)[2] and Computational Tree Logic[3]. The visuals taught in this course are similar to the visuals used in [26], which have circles and arrows pointing to the next circles on the right. The values of the propositions[4] in the circles are depicted as "p" for "p is True" and "∼p" for "p is False".

The Wikipedia page for LTL[32] has visuals for Linear Temporal Logic that have variables represented with symbols above dots with solid or dashed lines and arrows pointing to the next dot on the right. The proposition is present above the dot if it is True and not present if it is False.

WEST [9] displays Mission-Time Linear Temporal Logic (LTL over finite time bounds) and all possible satisfying assignments for variables over a timeline. It uses active checkboxes for True values and inactive checkboxes for False values. The timesteps are labeled, and the values to the right are forward time. This tool also has a regular expression visualization that separates the variables into comma-separated timesteps, using 1 for True values, 0 for False, and S for the value not mattering to satisfy a formula.

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[1] "True" or "False" data values.

[2] Linear Temporal Logic is a type of formal method that reasons about Boolean variables over a single timeline.

[3] Computational Tree Logic is similar to LTL, but it handles timelines as many possible branches that can be taken at any time step.

[4] Propositions are the semantic meanings of the Boolean variables. For example, r := "rockets are cool," means that r is replaced with "rockets are cool." "Rockets are cool" is the proposition, and r is the Boolean variable.

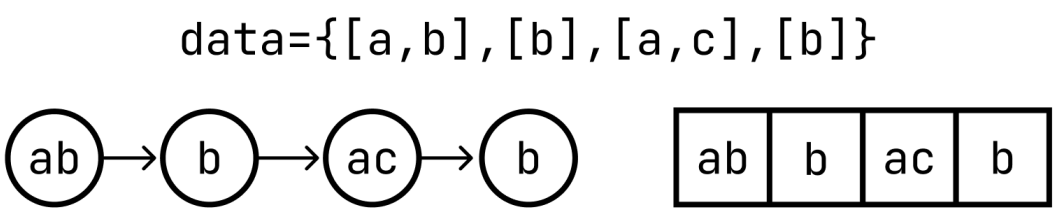

Figure 3 Circles with arrows pointing to the next time step are an inefficient use of space and present redundant information, which causes extra mental workload for users. If we know that the "forward" time steps are to the right of the current time step, then we can simplify the visualization of some Boolean data by removing the arrows and compressing the nodes to be next to each other. A variable is present if it is True at a timestep.

ltl2timeline [18] inputs an LTL formula and outputs a timeline. Each node contains the satisfying set of proposition assignments ("p" for "p is True", "!p" for "p is False"), with arrows indicating the progression of time to the right. Branching paths represent formulas with multiple possible futures, and boxes denote points of infinite repetition in the timeline.

Principles of Model Checking [4] shows empty circles with true formulas over the circles and lines with arrows pointing to the right to the next circle.

Notable Patterns

All of the visuals displayed represent Boolean values of variables representing propositional statements. All representations of nodes evaluate to True under some propositional statement (i.e., "It is true that p is false at this time."). All represent the progression of time as "to the right". 5 out of 6 representations use circles of some kind to represent their Data nodes. All representations that use circles also represent the movement of time with a line and an arrow.

Applying Design Techniques to Observed Patterns

Having arrows pointing to the next node is redundant on timelines with no branches because the direction of time progression does not tend to change once it is established. Timeline movement is the same direction that we are reading the words on a page (this may be the same for any reading direction, but that would need to be studied in future work). Unless it needs to be specified that the direction of time is changing (see figure 4 for an example), then there could be fewer symbols to display the movement. Figure 3 shows the difference between the two types of visualizations.

3 Current Progress and Findings

This section outlines two related studies done on timeline visualizations. The first is a pilot study for discovering commonalities and disparities in understanding between users of timeline visualization tools. The second is the first iteration of visualizing aggregate data for multiple runs of complex systems.

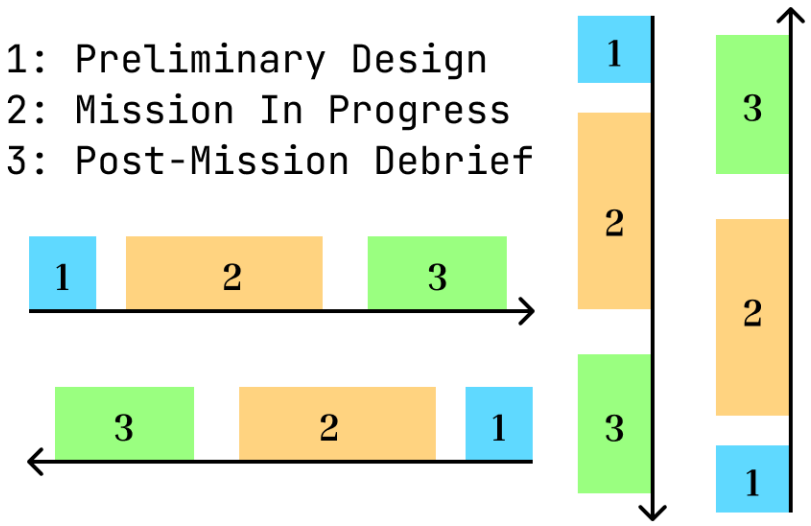

Figure 4 The orientation of sequential representations may influence the interpretability of time-oriented data in mission planning and analysis. This figure presents a simplified mission timeline across four distinct directional layouts. During the case study, one participant explicitly preferred a top-to-bottom timeline for aligning with their workflow. Understanding how cultural and contextual factors affect spatial-temporal reasoning may inform more effective visual design choices for systems engineering applications.

3.1 Pilot Study: Investigating the Understandability of Timeline Visualizations

A study by Knight et al. was done across two separate colleges, involving students from multiple backgrounds, including several individuals from the programming industry. Students were told to write a program from a single specification. The individuals were not informed that others had the same specification. The programs were then subjected to test cases and evaluated for correctness. The study found that regardless of college, background, expertise, and experience, several of the same mistakes were made in creating the programs. Knight et al.'s study demonstrates the concept that this investigation is based on: *Regardless of the region of learning, background, or experience, there are potentially common deficits and beliefs among individuals in a field of study* [15].

The work in progress presented in this section is the pilot study for finding commonalities in understanding timelines and answering the larger question, *"How do we best define usability for system engineers across disciplines?"*. The primary objectives of this pilot study were: 1) **To assess the impact of timeline direction on understandability:** Does the orientation (e.g., left-to-right vs. top-to-bottom) influence how users interpret time-oriented data? 2) **To evaluate how different visual representations affect comprehension:** How do variations in shape, structure, and layout impact user interpretation and usability?

Beyond these specific research questions, the study also served as an ideation process for refining future studies on time-oriented visualization, helping the authors identify promising approaches and potential pitfalls in time-oriented visualization design.

Methodology

The pilot study was conducted as a focus group, allowing participants to engage in discussions and provide qualitative feedback on various timeline representations. The visualizations presented were created from visualization patterns discussed in section 2.

Participants were presented with multiple timeline representations and asked to evaluate their clarity, usability, and effectiveness in communicating time-dependent information. The study followed a standard focus group process to facilitate replication in future research:

1. **Introduction and Background:** Participants were given an overview of the study and its objectives.
2. **Presentation of Timeline Visuals:** Various visualizations were shown, including directional orientations and structural variations[5].
3. **Group Discussion and Feedback:** Participants shared their thoughts, highlighting aspects they found intuitive or confusing.
4. **Conclusion and Reflection:** A debrief session allowed participants to articulate their overall impressions and suggest potential improvements.

Findings and Insights

Common visualizations used in formal methods from section 2 were confusing, such as those that resembled automata (see figure 5). This makes sense from two different sides: 1) The people who originally created the visualizations for temporal logic timelines came from backgrounds that used automata [25], and the historical visualizations linger in today's representations. 2) The people in the focus group also have backgrounds that involve the study of automata. Even though they work with both LTL and automata visualizations regularly and understand the context of both types of data, using similar visuals can be confusing regarding the intended meaning. This confusion may appear for other users because the intended demographics to be studied include people who have also most likely experienced automata in their formal education. Such confusion highlights the importance of designing timeline visualizations that are distinct from other visual representations commonly used in formal methods and systems engineering.

Discussing multiple visualization types encouraged participants to generate new ideas and reinforced visualization techniques they had found useful in other contexts. This collaborative approach encouraged deeper reflection on usability and prompted the identification of effective timeline representations. One participant commented about how their vision disabilities affect how they view timelines on screens and suggested user interface visualizations that have made their work easier for other applications such as having multiple options for visualization that could be selected for users in a settings menu, such as changing color pallets, timeline directions, and node shapes. For scalability, a suggestion that was positively received among the participants is that for larger data sets, when zoomed out, the data would be abstracted and less detailed so as not to overwhelm the user, and the details would return when zoomed in.

[5] The visuals used for the study can be found here: `https://forms.gle/AC4HNuUgpUxpXeuSA`. Personal information is not collected through this link.

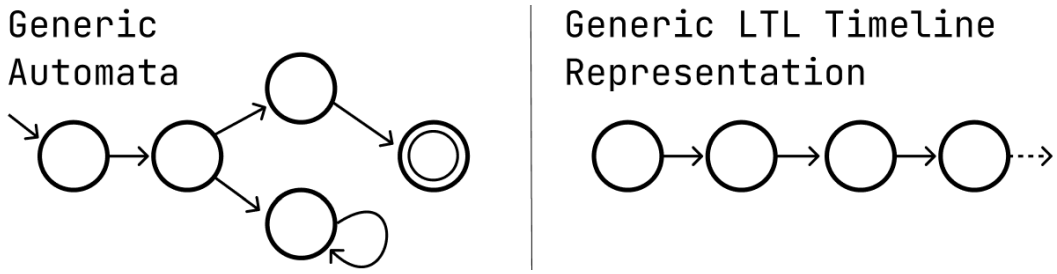

Figure 5 Automata consist of distinct nodes, each representing a system state defined by a specific assignment of variable values. To move between nodes in the automata, the state must change in some way that reflects the assignment of the variables in the next node. A common representation of LTL timelines is similar to assignments of variables at each node, but that is where the similarities end. The LTL timeline is a statement of fact about the variables rather than a choice to be made in the system.

Limitations and Future Work

The two main limitations to this study are 1) **Single research method:** While valuable for qualitative insights, a focus group does not provide quantitative measures of usability or performance. 2) **Limited participant diversity:** The study was conducted with a small group (about 8 people) from a single research field, meaning the results are inherently biased toward their particular training and experiences. Expanding the study to include more participants and participants from different disciplines and professional backgrounds will be necessary for generalizability.

Future work will expand upon these findings by conducting larger-scale user studies with a more diverse participant pool. Demographics to be explored include any individuals who will work with these timeline systems either as designers or users, including (but not limited to) computer scientists, mathematicians, mechanical and electrical engineers, and visual and user experience designers. Future work will also incorporate quantitative usability metrics such as task-load analysis, and refining visualization techniques based on this and future studies, as well as more research on visualization techniques currently being used that were not considered for this study, such as [16, 20, 19, 31, 21].

3.2 Aggregating Timeline Verification Data for Remote Space Systems

Timelines uploaded to remote, uncrewed systems, such as those planned for NASA's Lunar Gateway, must be verified to ensure they are conflict-free and do not pose risks to mission success. Given the complexity of such systems, the consequences of executing a single timeline cannot be determined with certainty due to the numerous variables present at any given time. One approach to verifying the reliability of a timeline before deployment is to simulate its execution under a wide range of possible conditions. Since these conditions could encompass hundreds or thousands of variations, understanding the aggregate results of multiple runs is essential for evaluating the robustness of a timeline.

Aggregate analysis of timeline simulations is critical in remote system operations, where immediate intervention is not possible. Once a timeline is uploaded to a distant uncrewed system, such as a spacecraft, any errors may persist for a significant duration due to round-trip communication delays [13]. Therefore, it is essential to identify potential issues before deployment. For instance, if failures consistently occur at a specific time step across all simulations, pinpointing the failure's location and cause is invaluable for debugging.

Aggregate Timeline Data							Total
Time Step	0	1	2	3	4	5	6
Number of Failures	0	0	0	15	5	0	20
system_1				T	F		
system_2				F	F		

Figure 6 The table represents time steps as columns, with the total number of failures at each time step indicated by varying shades, where darker shades denote a higher frequency of failures. system_1 and system_2 are Boolean variables representing system statuses that evolve over time. Each cell displays the most common failure state (T for True or F for False) observed across all runs. The usability of this visualization has been preliminarily assessed through informal evaluation. However, key criteria have been identified to be useful to systems engineers, including violated time steps and variables, violation frequency, and the underlying causes of this violation.

Conversely, if all possible executions result in successful operation without severe consequences, this outcome should be clearly conveyed to engineers. Such analysis helps determine whether problems stem from flaws in the timeline itself or from underlying system issues, ultimately supporting safer and more reliable mission planning.

Current Progress

Several approaches to aggregating verification results have been explored to address this challenge, including bar graphs, numeric charts, and ideas taken from the preliminary studies done in section 2. The most promising method identified thus far is displaying the system data in a table highlighting the number of failures at given time steps, and emphasizing more failures at a time step with a heat-mapping. Figure 6 shows an example visualization of aggregated data.

Implementation

This approach uses R2U2, a runtime verification framework designed for safety-critical systems [14]. Timeline data is processed through R2U2, which generates verification results based on predefined specifications. These outputs are then structured into a data representation suitable for visualization; the current implementation uses .csv files. The visualization tool[6] interprets this structured data to highlight trends, recurring failures, and overall system behavior across multiple timeline executions.

Limitations and Future Work

One limitation of the current approach is the challenge of efficiently displaying timeline data. The tabular representation may contain numerous empty cells, which can be beneficial for visualization by highlighting The tabular representation may contain numerous empty cells, which can be beneficial for visualization by reducing visual clutter, drawing attention to meaningful data points, and highlighting sparsity in variable activity over time (see

[6] the current version can be found here [29]

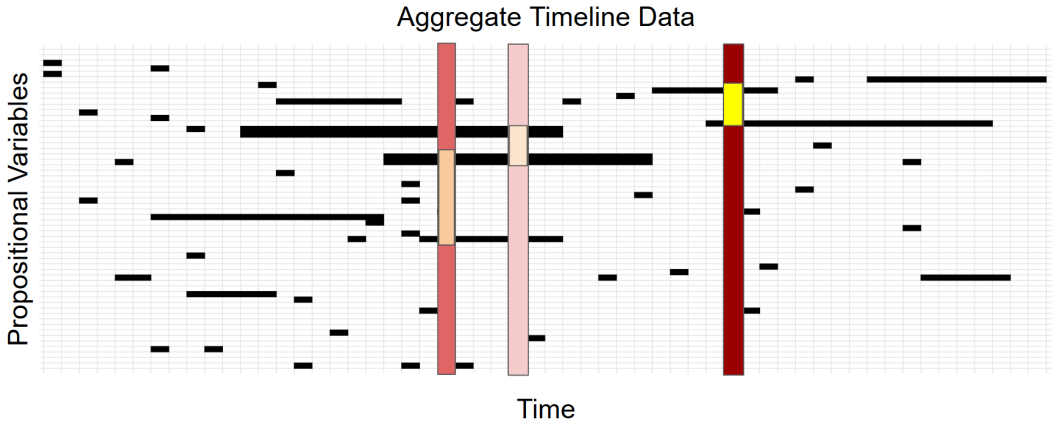

Figure 7 Scalability is critical, as real-world systems often involve hundreds or thousands of variables across hundreds or thousands of time steps. A visualization that works well for small examples may become cluttered or unintelligible at larger scales, limiting its usefulness in practical analysis and decision-making. This visual example is still relatively small compared to real-world systems. The markings inside the red highlighted areas represent areas of propositional failures at those timesteps to help find key variables for analysis.

figure 7). However, this format is not optimal for data storage, as it may introduce inefficiencies in handling large datasets. Additionally, navigating and identifying specific issues may become cumbersome if the timeline is too long. Future work will explore alternative visualization techniques that balance readability and data density, such as adaptive filtering, interactive zooming, or alternative representations that prioritize critical information without overwhelming the user.

Currently, this approach has not been tested on real-world mission data, nor has it been validated with large-scale datasets. Future work will focus on acquiring real-world datasets to further evaluate the effectiveness of the aggregation method. Additionally, usability studies with systems engineers will be conducted to assess how well these visualizations support debugging and decision-making in mission planning. The ultimate goal is to refine the visualization techniques to improve interpretability and ensure that timeline verification tools meet the practical needs of system engineers.

4 Conclusion

Timelines play a crucial role in space exploration, and their importance will only grow as missions become more automated and venture farther from Earth. The criticality of understanding timelines lies in the fact that once sent into uncrewed space systems, there is a round-trip delay before identifying and addressing any unforeseen issues with the timeline commands.

The patterns discovered in the literature review have been applied to an initial usability study, which revealed confusion in understanding due to overlaps in visualization techniques between areas of study. This work also takes an initial step in visualizing aggregated data of complex systems for understanding and debugging complex systems and verifying timelines before uploading them to uncrewed spacecraft. The visuals presented identify critical aspects for making the visuals useful for systems engineers.

While this work focuses on space systems, its findings and future work have broad applications in other fields where timeline verification and understandability are essential, such as designers of timeline systems for engineers and those working with uncrewed aerospace, underwater exploration, and emergency response vehicles. Future work for this research includes developing educational curricula that prepare individuals to work with these critical systems by identifying common (mis)understandings in timeline interpretation.

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NEREUS: An Assistive Decision Support System for Real-Time, Adaptive Route Guidance in Extravehicular Navigation Activities on the Lunar Surface

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Abstract

Extravehicular Activity (EVA) is one of the most complex operational endeavors during human lunar exploration. A key aspect of successful operations involves adapting procedures to address unexpected hazards on the lunar surface. Current route mapping systems rely heavily on static navigation planning around craters, high elevations, and extreme weather conditions to accomplish pre-defined mission objectives. However, the high-resolution data necessary for reliable route mapping is often unavailable. To address this challenge, we have designed NEREUS, a Decision Support System (DSS) that helps EVA operators on the ground respond to anomalies faster by simulating multiple alternative routes in parallel and visualizing trade-offs in consumable resources, speed, and safety as well as impact on overall mission timeline. The system offloads computationally intensive tasks like calculating the impact of evolving hazard data, allowing operators to focus on higher-level decision-making.

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1 Introduction

Lunar Extravehicular Activity (EVA) involves risks that necessitate thorough contingency planning, comprehensive training procedures, and precise navigation mapping to ensure a successful mission. The NASA Artemis mission has made clear efforts toward sustainable human presence on the moon, and eventually Mars [24]. Adaptability is crucial in enabling autonomous and safe human operations during EVAs, as current navigation systems still rely heavily on manually mapped, static routes derived from simulated or low-resolution data of the lunar surface. During Apollo 11 in 1969, obstacles undetected during mission pre-mapping extended the descent time 90 seconds, demonstrating how small mapping inaccuracies could jeopardize mission success [13]. Similarly during EVAs, undetected hazards like craters, large rocks, or other surface anomalies may require in-the-moment re-evaluation of pre-planned routes. To address this, we have designed a prototype Decision Support System (DSS) for adapting routes in response to ambiguous risk scenarios, thus allowing operators to evaluate safety and time-critical trade-offs across multiple routes simultaneously. While the prototype is intended primarily for ground EVA operations, it is a first step toward on-surface adaptability by making data more interpretable and making trade-offs more intuitive. This paper describes the design of NEREUS (Navigation, Evaluation, and Route Environment Understanding System)[1], an adaptive route planning system that supports real-time decision making and lays the groundwork for future human autonomy in space exploration.

1.1 Current Approaches to Navigation

Current maps of the lunar surface captured by the Lunar Reconnaissance Orbiter (LRO) only display elevation accuracy up to 10 meters leaving smaller obstacles undetected [15]. Mapping methods still require operators to design high-detail navigation routes months to years in advance, while NASA spends hundreds of hours to verify hazardous regions on maps, further extending mission timelines [2]. Despite this, topological imagery from the LRO still cannot capture small nuances in the terrain. In response, NASA has developed the Personalized EVA Informatics and Decision Support platform (PersEIDS) to bolster situational awareness and anomaly tracking as a decision support system during navigation [17]. However, because this platform still requires mission control operators to manually compare route data to pre-planned data, the potential remains for significant delays when anomalies are detected.

1.2 Operator Role and Mission Context

Human space missions involve close collaboration between astronauts and support staff on Earth. “Operators” in ground stations such as the Mission Control Center (MCC) at the Johnson Space Center manage logistic plans and communicate procedures to the astronauts. Each operator typically oversees a specific function such as monitoring consumables, mobility, or navigation. Operators and astronauts communicate with each other through shared digital displays and verbal communication. Operators currently use a combination of paper checklists, biometric displays, and verbal updates from other operators to make constant decisions during hours of operation [20]. On top of their existing responsibilities to advance the mission progress and coordinate routes, they are also constantly monitoring the Astronaut Crew’s (hereafter referred to as the “EV Crew”) safety and developing new procedures in the event of emergencies [21].

[1] Nereus is the name of the Greek God of the Sea known for his wisdom and ability to change shapes, which inspired the name of our adaptive navigation system.

Operators must contend with a large amount and variety of incoming information, evolving mission contexts and environmental conditions, and the responsibility to make potentially life-and-death decisions. These challenges are compounded by communication delays with the EV crew, which could reach up to 10 seconds in future lunar missions [3]. This leads to confusion and communication gaps which could jeopardize their safety during emergency scenarios. Reducing operator workload and increasing EV crew autonomy are important strategies for reducing risk, building resiliency, and improving mission outcomes.

1.3 Challenges to Decision-Making

The ability to assess hazards and update procedures in real time is crucial during EVAs. The current operator workflow requires a complex timeline including risk assessment, communication across departments and EVA's, and integrating new procedures into a checklist system [11]. Pre-mapped routes need to be manually evaluated against environmental data like dust storms, changing lighting conditions, and the mission timeline, which slows down risk assessment and delays the mission overall. This evaluation process requires shifting attention across dynamic conditions and evaluating alternative hypotheses, increasing pressure on working memory and preventing the operator from making effective decisions [4].

From a cognitive standpoint, the data evaluation process is often ambiguous and stressful for operators, impacting the quality of their decisions. Operators must evaluate trade-offs and risks based on incomplete and potentially inaccurate data. Accurate assessment requires complex calculations, currently with little computational support. Operators struggle to develop a precise representation of the current mission environment, limiting the effectiveness of their decisions [27]. In EVA operations where data may be delayed or incomplete, manual and optimization-based decisions become risky [5].

The current Mission Control System (MCS) setup includes a Baseline DSS and an Advanced DSS (Marvin), which includes three views on three different screens: Life Support Data Display (LSS) showing biometric data, Timeline Management System displaying the timeline and procedures, and a Communication Log for documenting procedures [20]. Our DSS system complements these existing workflows by integrating a lightweight *decision layer* focused exclusively on navigation-based trade-offs. While Marvin oversees the entire mission timeline and provides *observability* over mission progress, NEREUS introduces a spatial reasoning system that allows operators to actively *compare* contingency plans based on time, resource, and risk impact.

2 Adaptive Navigation System

2.1 Decision Making Workflow

The NEREUS decision-making process will align with the three elements of Endsley's Situational Awareness (SA) Model, which includes perception of the current situation, comprehension of trade-offs, and prediction of future situations [9]. The NEREUS platform decision tree is outlined in Figure 1, which visualizes the primary decision touchpoints operators encounter during an emergency scenario to select a final adapted route layout.

As an EVA progresses, new and higher-fidelity environmental data will become available from EVA crew reports, real-time video, and other *in situ* sensors (e.g. high-resolution LiDAR mapping). As new features are detected and added to the mission maps, potentially hazardous objects will be segmented on the Mission Control System (MCS) Map in a color scale based on NASA's guidelines for Human-Computer Interaction and Interface Design,

where red indicates the highest severity and orange indicates a warning (see section 3.4 for more details) [22]. Characteristics of the detected object like the detected rock composition, steepness, and elevation will be displayed on the operator interface. Instead of displaying raw numbers for biometric and battery data, labels will indicate the danger level of each element (i.e. "normal" for safe levels, and "dangerous" for low levels). NEREUS will automatically update assessments of potential navigation routes from available hazard data and current mission status. The system will choose candidate routes that optimize different mission parameters (e.g. safety, speed, and conservation of resources), and present them to the operator with the analysis results for each route. The NEREUS display will support the operator as they make the final decision with the given information and fill in the gaps where the prediction model may fall short.

To maintain mental continuity between the route changes and impact on the procedural timeline, we implemented a mini procedure checklist module on the interface. While it does not fully replicate the full timeline system, it allows operators to quickly reference the impact of route changes on operational execution without crowding the interface. The full interface-level implementation is discussed in section 3.3.

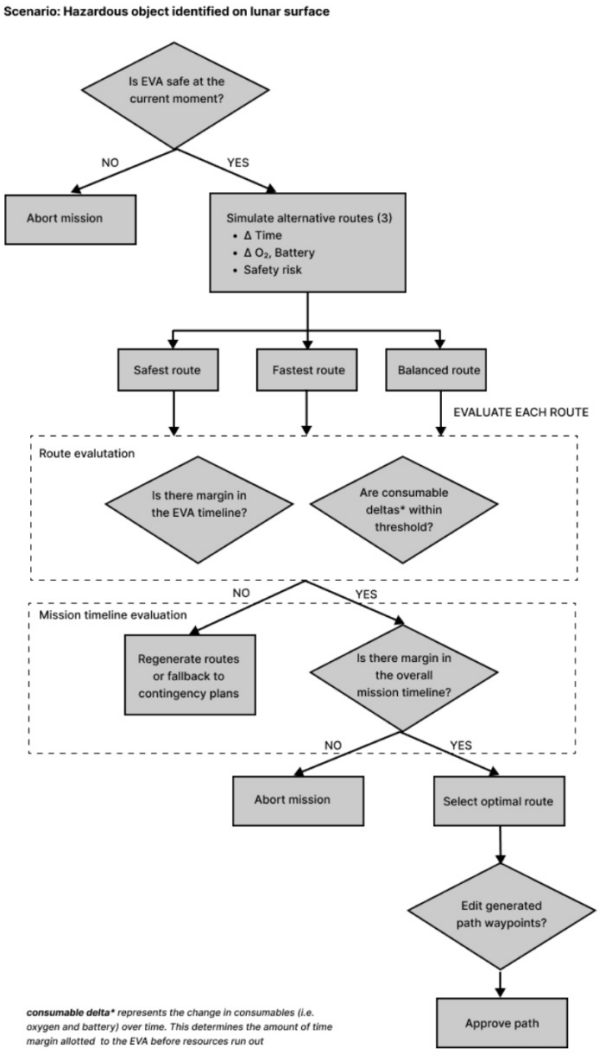

Figure 1 Decision Tree outlining operator path selection during EVA anomaly detection.

2.2 Route Evaluation System

To support operators in making more timely decisions, we propose a computational route evaluation system that integrates a real-time risk assessment model with a route-mapping system. This system provides dynamic route evaluation based on evolving environment information in order to support more accurate decisions. The core of this system is the Probability of Return Model (PoR), which evaluates the likelihood of an EVA returning to base. To calculate this PoR, the model synthesizes key environmental and astronaut status data to ultimately determine overall risk and mission timeline impact.

2.2.1 Route Generation and Search

The system generates candidate routes through a brute-force A* search algorithm. A* is in the class of path-finding algorithms that support finding an optimal path given various environmental constraints [12]. The A* algorithm has been shown to have a number of advantages, including being able to efficiently find optimal solutions in dynamic environments [30]. The suggested implementation of the A* cost function would penalize hazardous terrain:

$$f(x) = g(x) + h(x) + \lambda \cdot r(x) \tag{1}$$

where $g(x)$ is the cost from the start to node x, $h(x)$ is the heuristic to the goal (e.g., Euclidean distance), $r(x)$ is the risk score at node x, and λ is a tunable weight penalizing high-risk regions.

By running multiple iterations of A* with a distribution of values for λ, the system is able to comprehensively generate a set of viable routes.

2.2.2 Evaluating Probability of Return

Once routes have been generated, the proposed Probably of Return (PoR) model would generate a risk score for each candidate route. The PoR model is a lightweight machine learning model that relies on a learned weighting system based on various path characteristics identified as key considerations for EVAs (like expected energy cost and oxygen use) [10, 1]. The PoR is estimated as:

$$\text{PoR}(p) = \sigma(\mathbf{w}^\top \mathbf{x}_p + b) \tag{2}$$

where $\sigma(\cdot)$ is the sigmoid activation function, $\mathbf{w}$ is the learned weight vector, $\mathbf{x}_p$ is a vector of parameters for the current route, and b is a bias term. This model allows for real time risk evaluation of proposed paths.

2.2.3 Route Selection

Finally, the system selects three primary route candidates that optimize for different weightings of speed and safety. The primary candidate routes will include the shortest route (based on distance), the safest route (based on highest PoR), and a balanced route that considers both speed and safety. This trade-off is captured with a composite cost function:

$$C(p; \alpha) = \alpha \cdot T(p) + (1 - \alpha) \cdot R(p) \tag{3}$$

where $T(p)$ is the estimated time to traverse path p, $R(p)$ is the aggregated risk score from the PoR model, and $\alpha \in [0, 1]$ allows operators to tune the priority between speed and safety.

The primary candidate routes will be presented to the operator, who will make the final route selection. Operators can also manually draw alternate routes on the interface, which are then evaluated and assigned a probability of return. This allows greater flexibility and can act as a fallback in the event of errors or un-modeled considerations.

3 Interface Design

3.1 Design Methodology

The interfce design process was curated around two primary goals: a) translating complex data into a more human-understandable representation and b) supporting collaborative decision making across the Operator, Astronaut, and AI. To accomplish these goals, we first experimented with ways to support operators in calibrating their trust in the AI agent. To support collaborative decision making, we designed the system using the human-autonomy teaming approach [16] by borrowing principles of adjustable autonomy systems which allow operators to dynamically override or change AI outputs. This is explained in more detail in section 3.2.

We began the design process by conducting semi-structured interviews with 9 domain experts, including Simulation Engineers, Astronaut trainees, and HCI Researchers from the Johnson Space Center and Ames Research Center. Post-analysis revealed two recurring insights:

- There is a lack of human-understandable data representation
- Protocols are fixed and unreliable during emergencies

To address the issue of data understandability and procedure adaptability, we designed the interface in adherence to NASA Design Principles around system transparency and adjustable autonomy outlined in the Human Integration Design Handbook (HIDH) [22]. This includes MIL-STD-1472F Section 5.14, a common military design standard used by the Department of Defense, which outlines computer interface design principles such as clear labels for system status and allowing operators to back out of decisions [6]. Additionally, we applied standard User Interface Design Principles such as visibility over system status and maintaining operator controller outlined in Jakob Nielsen's Usability Heuristics [25]. These principles helped guide us to create an understandable and fast-to-learn interface.

3.2 Operator-AI Collaboration

To support collaborative Human-AI decision-making during the route selection process, we implemented the Adaptive Calibration Trust Model which continuously tracks and communicates anomalies in the simulated routes to the operator [26]. We designed a digital communication system that facilitates a common operating picture through trust calibration cues (TCC's) which signal when to rely on the model's output or intervene. For example, the risk trend lines and color palette for each route card indicate when the model predicts elevated risks and recommends operator input, at which point the operator can either update the path or override it entirely. An explicit text box also points out hazards that cue operators to intervene.

During an emergency rerouting scenario, the model assesses different paths and procedure options to display on the interface (described in section 2.2). Each path is annotated with parts of the path where the model is uncertain to support system transparency. Paths are accompanied by a risk profile where battery, oxygen, and other consumables are represented as change over time, with upwards and downward symbols showing trend over time.

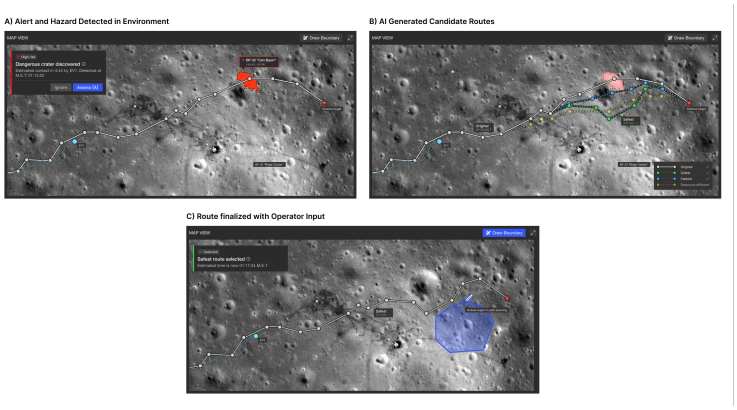

Figure 2 Sequence of user interactions the operator takes with the map. A) When a hazard is detected, the model will visually segment the object and throw an alert on the interface B) The operator can draws lines around areas to include in the routes generated C) The output routes are displayed combining the operator and model inputs.

Figure 2 represents the sequence of interactions between the operator and the model used to generate candidate routes. When a new hazard is identified through the EV Crew's camera feed, an alert will appear on the interface (Interface A). When the operator approves the generation of paths, three candidate routes will appear (as described in section 2.2), each labeled with their corresponding changes to the timeline margin (Interface B). Finally, the operator can select the ideal path based on their personal judgment and draw and additionally draw a boundary around regions they want to be included in the output path (Interface C).

3.3 Information Design

We opted for a single, fully-equipped interface as opposed to progressively disclosing information since this is better aligned with the Flight Controller Problem Solving Model which involves assessing a situation holistically across multiple way-points, procedures, and variables [19]. The path simulation represents one activity, such as ingress, that would be represented on a broader mission timeline for encapsulation. Each route is organized as a card mapped to each stage of the timeline, building on the familiar file-like mental model employed by NASA's OpenMCT framework [23]. While not widely used for live EVA operations, this model reflects how operators parse through paper timelines and procedures. In order to reflect familiar sequential and temporal mental models, we patterned our decision-making workflow on the procedure checklists common in mission control rooms (see Figure 3 for an example).

We designed the main simulation interface to provide a visualization of the candidate routes with associated route information in order to support appropriate causal reasoning and situational awareness [14, 9]. The interface is shown in Figure 4.

In Figure 5, we show how the procedures module displays modified tasks as interactive cards embedded in the original task list. Added or removed procedures are displayed as new cards on the existing procedure list, which the operator can approve or make revisions on, providing additional decision context and options. Each card also shows the impact on the mission timeline. These task cards support a holistic understanding of the mission timeline while enabling real-time adjustments as the mission progresses.

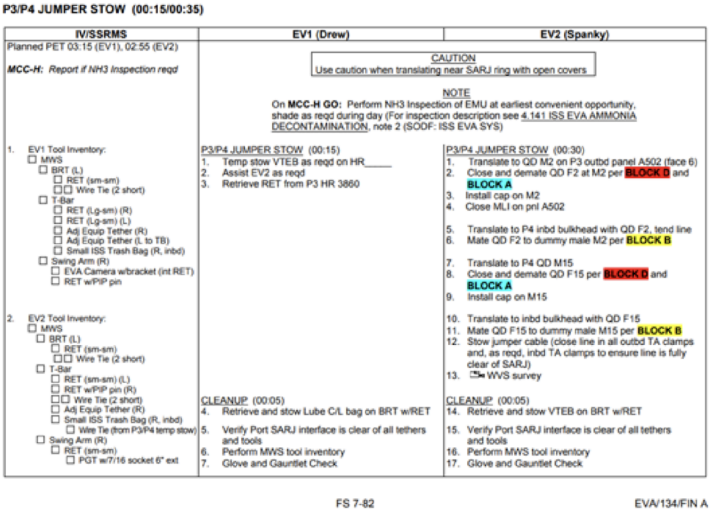

Figure 3 Sample sequence of operator interactions with the map interface when detecting and responding to hazards.

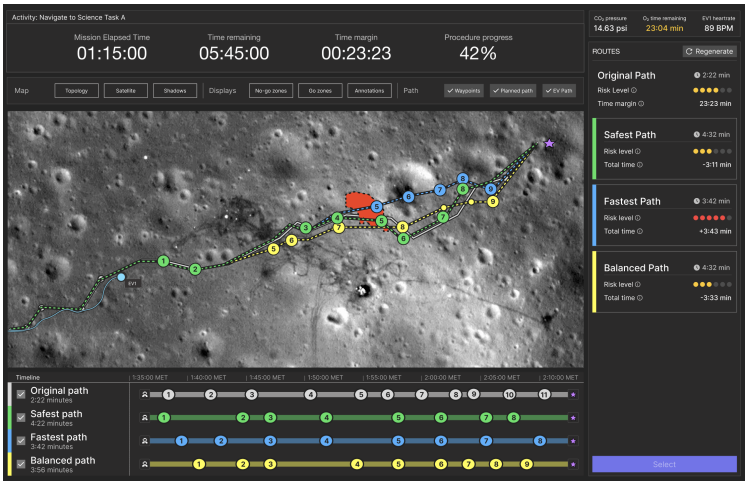

Figure 4 Mission Control Interface displaying navigation route recommendations for the operator.

3.4 Data Layers and Anomaly Representation

The map located at the center of the interface visualizes the terrain, hazards, and chosen routes. Operators can import pre-planned routes and map features into the interface. Craters and terrain features are named based on the International Astronomical Union (IAU) Nomenclature standards which specify common naming conventions [28]. Additionally, we referenced the MIL-STD-2525 symbology standards, a military design standard used by NASA, to represent the map under a shared visual standard such as using Main Supply Route (MSR) symbol set to represent the original path and the Alternative Supply Route (ASR) set to represent all alternate paths [7].

To support rapid anomaly detection, hazardous regions are enclosed in a red polygon based on a combined representation of the terrain measured on steepness, traversability, elevation, weather conditions, and pre-identified risks from the terrain (MIL-STD-2525D

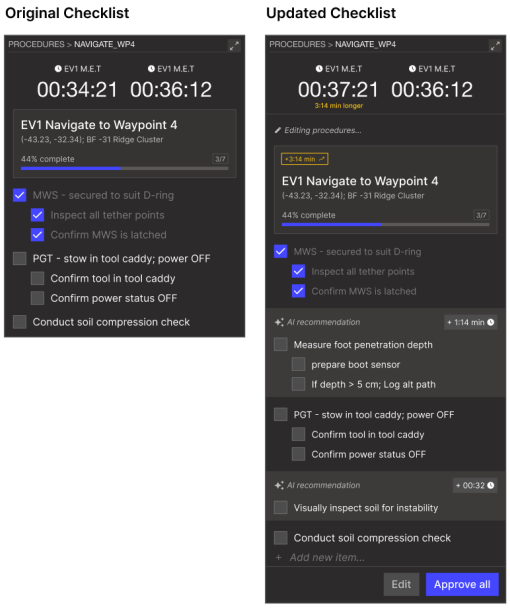

Figure 5 Sample Paper EVA Procedure Checklist Document used during STS-134.

Symbol 270200 – Obstacle Zone). In addition, the risk levels are visualized using a color scale derived from the NASA Risk Matrix [8], which is the standard framework for hazard assessment visualized in Figure 6. The operator may also "drill down" on specific elements on the map, such as the waypoints, to view more details about them without overcrowding the main user interface. By representing the terrain based on risk level, this adds an extra layer of context and ultimately supports the selection of paths that optimize for mission safety.

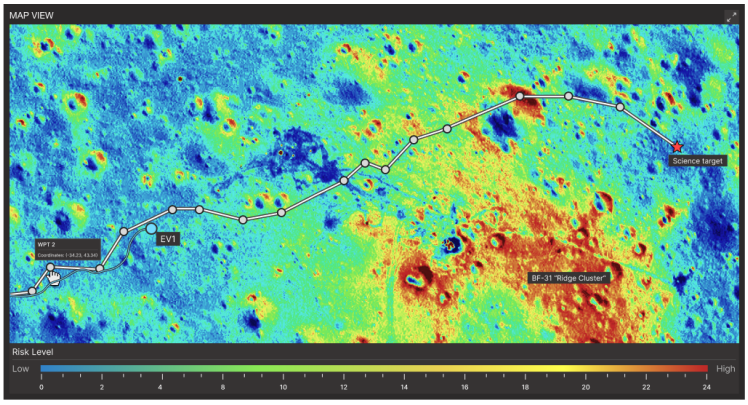

Figure 6 NASA Risk Matrix for hazard assessment visualization.

4 Usability Testing

To evaluate the decision-making process of the NEREUS platform, we conducted usability tests with HCI experts and NASA. We aimed to evaluate NEREUS' performance in decision-making speed, accuracy, and confidence compared to the baseline checklist systems. We also

tested the clarity of information displayed, following the "just-in-time" framework to ensure that data is only surfaced when the user needs it to make a decision [8].

We ran 4 synchronous usability tests, each lasting 45 minutes. We presented the participants with the prototype over zoom and observed their interaction patterns as they moved through the screens. We used the following scenario to prime the user before each testing session:

> *Imagine you are a Mission Control Operator at the Houston Mission Control Center, monitoring an ongoing extravehicular activity operation for a team of astronauts on the moon. Your team encounters various hazards in the terrain that require you to reroute the path on the NEREUS decision support interface as the EVA Crew navigates the terrain. Your goal is to help the EVA crew adapt to changing terrain hazards by selecting the most appropriate route using NEREUS.*

At the end of the session, we asked each participant to rate their experience with the system on a simplified version of the NASA-TLX Index, which calculates the participant's cognitive load on a scale of 1 to 7 [18]. We also added two additional parameters to measure the participant's confidence and trust in the system. The results are shown in Table 1.

Table 1 Mean and standard deviation of subjective workload and trust metrics.

	Confidence	**Trust**	**Mental Demand**	**Effort**	**Frustration**
Mean (μ)	5.25	6.0	4.5	4.0	1.5
Std Dev (σ)	0.356	1.414	2.121	2.829	0.707

Overall, participants consistently reported high levels of confidence and trust in the system with low frustration levels . However, participants reported varying degrees of mental demand ($\sigma = 2.121$) and effort ($\sigma = 2.829$), suggesting that the system requires a higher level of expertise to comprehend. It may benefit from information simplification and adopting a shared language across all NASA employees.

5 Reliability of NEREUS Assessments

There are several challenges such as communication delays, incomplete data, and radiation interferences on data transfer, that impact the reliability of the route predictions. In these circumstances, it's crucial for the operator to know when they should adjust or override the AI recommendations entirely.

We used a combination of visual, textual, and audio TCCs to communicate uncertainty quickly across multiple dimensions and receive constant signals no matter the focus of attention. For example, a risk trend line is displayed for each generated route card to indicate when operator input is recommended to mitigate high-risk outputs from the model. Following MIL-STD-2525D, uncertainties in the terrain are marked with crosshatch overlays and dashed route segments to indicate regions where the data is incomplete or obstructed. Each route also contains an explicit text summary pointing out risks in the procedure change. This summary is designed to match mental models of standard operating procedures (see Figure 3), supporting quick recognition and recall of procedural best practices. The goal of this system is not to make decisions for the operator but rather to display context-based cues to prompt pattern recognition and recall of operational heuristics, ultimately supporting operators to make better decisions. Displays of the TCCs are shown in Figure 7.

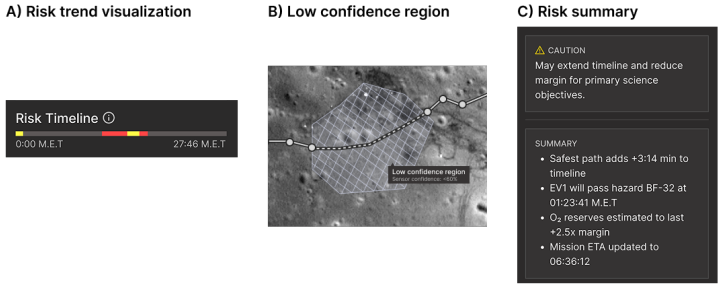

Figure 7 Trust Calibration Cues (TCCs) in NEREUS. A) Risk trend visualization over time for each route B) Low confidence region segmentation on a map and C) Risk and route summary.

In our user studies, participants consistently noted that the risk indicator bars informed their final decision the most. Multiple participants expressed confusion about technical terminology like MET, time margin, and time remaining and had different interpretations of what each meant. Future designs should incorporate a more standardized terminology system. Visual overlap and mixed interpretations of route colors also made it difficult to quickly identify and compare routes on the map. Future designs should incorporate more customizability like incorporating colorblind-accessible visuals and a set of data layers that fit current mental models like Google Maps. Critical status indicators like oxygen and battery were also overlooked since they were nested under other panels. Future designs should have a persistent display of biometric and status data.

6 Future Work

In the future, we plan to test and validate the design concept in realistic mission environments, improve the current interface, and expand the DSS across more scenarios.

Validation of the DSS and PoR model will be conducted by running live simulation scenarios with expert operators. The goal of this stage is to test the DSS' ability to adapt during a realistic mission environment and test whether mock operators could effectively simulate and select a new path given a navigation scenario.

Further testing will include validating and extending the Trust Calibration Cues (TCCs). We also plan to incorporate enhancements in symbology and color schemes to align with Web Content Accessibility Guidelines (WCAG) to improve clarity and interpretability of the interface [29].

While the focus of this iteration has been on operator decision making, we are also actively working on developing a companion system to support operator-astronaut communication and autonomous decision making by EV crew. This system will be based on a head-mounted display (HMD) designed to augment the astronaut's headset by projecting alerts, segmenting hazards, and providing audio decision support. We plan to embed the decision logic outlined in this paper with the HMD.

Finally, we hope to adapt NEREUS to more complex, multi-variable emergencies. While the DSS is currently designed exclusively to support navigation, we plan to extend it to support a wider variety of mission planning tasks and anomaly scenarios (such as communication loss and dust interference). Since the ultimate goal of the Artemis Program is to support sustained human life on Mars, we plan to expand the system to a full autonomy support suite. This will enable expanded adaptation capabilities and semi-autonomous operation with more extensive communication delays.

7 Conclusion

The NEREUS Decision Support System proposes a decision-making framework and corresponding interface for real-time navigation adaptation during anomaly detection. The system presents a hybrid Human-AI Collaborative decision-making framework that employs novel ways to visualize hazards in the terrain and recommend multiple routes in parallel based on key mission-relevant trade-offs. Usability test participants consistently reported reduced frustration and high trust ratings for our system's final output. However, effort expenditure and complex terminology increased mental effort, presenting an area for future research. Our paper presents an early prototype that can lay the groundwork for future EVA decision tools for ecosystems with higher communication delays under the Artemis Program and future Mars expeditions.

8 Contributions

Jasmine Q. Wu led the conceptualization and design of the NEREUS platform, decision-making framework, and conducted all early user research studies and usability tests. She also led manuscript preparation and supported the design of the PoR model. Andrew J. Hwang contributed to the route simulation model, including the programming logic and display of candidate routes. He also assisted in manuscript preparation. Matthew J. Bietz provided critical feedback and helped shape the research, analysis, and manuscript.

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Movement in Low Gravity (MoLo) – LUNA: Biomechanical Modelling to Mitigate Lunar Surface Operation Risks

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Abstract

The Artemis programme seeks to develop and test concepts, hardware and approaches to support long term habitation of the Lunar surface, and future missions to Mars. In preparation for the Artemis missions determination of tasks to be performed, the functional requirements of such tasks and as mission duration extends whether physiological deconditioning becomes functionally significant, compromising the crew member's ability to perform critical tasks on the surface, and/or upon return to earth [MoLo-LUNA – leveraging the Molo programme (and several other activities) – could become a key supporting activity for LUNA incl. validation of the Puppeteer offloading system itself via creation of a complementary MoLo-LUNA-LAB. Furthermore, the MoLo-LUNA programme could become a key facilitator of simulator suit instrumentation/definition, broader astronaut training activities and mission architecture development – including Artemis mission simulations. By employing a Puppeteer system external to the LUNA chamber hall it will optimise utilisation and cost-effectiveness of LUNA, and as such represents a critical service to future LUNA stakeholders. Furthermore, MoLo-LUNA would generate a unique data set that can be leveraged to predict de-conditioning on the Lunar surface – and thereby optimise functionality, and minimise mission risk – including informing the need for, and prescription of exercise countermeasures on the Lunar Surface and in transit. Thus, MoLo-LUNA offers a unique opportunity to place LUNA, and ESA as a key ongoing provider of evidence to define, optimise and support crew Artemis surface missions.

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1 From Apollo to Artemis

The Artemis programme aims to place the first "boots on the Moon" since Apollo 17 in 1972. Apollo missions could be characterised as demonstration missions – dashing to the Lunar surface and back. In contrast, the Artemis programme seeks to develop and test concepts, hardware and approaches to support long term habitation of the Lunar surface, and future missions to Mars. In preparation for the Artemis missions, crew tasks need to be defined, whilst considering their functional requirements, not least because as mission durations extend physiological deconditioning may become significant, compromising a crew member's capability, and/or performance on the surface or upon return to earth [56].

Overall mission architecture including time in transit, and any stay on the Lunar Gateway must also be considered as microgravity (µg) is despite exercise countermeasures associated with multi-systems physiological deconditioning [57] – albeit with significant intra-individual variability [59]. As such it is critical to define the functional requirements of any task related to lunar surface missions (including emergency tasks), assess crew capability, predict task-relevant physiological de-conditioning, and thereby determine the potential functional

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implications prior to sustained Artemis missions. Such knowledge is critical not only to minimise task failure, but optimise task/tool design, prevent injury, and determine the need for, and if so, requirements of surface exercise countermeasures.

Initial Artemis missions are scheduled to involve Lunar surface sojourns of approximately 6 days, with the objective to extend missions as fast as supporting infrastructure and crew capabilities permit. In the Apollo mission reports, crew reported few issues post-flight, medical evaluations were relatively unremarkable, whilst aerobic capacity and orthostatic tolerance were reported to be at pre-flight levels after a couple of days [66]. However, Artemis will be in longer than Apollo missions (Apollo 17 was 12-d and 14-hrs) with longer transit times, even without accounting for a stay on the Lunar Gateway.

During transits (in the Orion capsule) crew will use a NASA Flywheel device although the exercise stimulus it will provide is incomparable to that generated by the current International Space Station (ISS) countermeasure suite provided by the Advanced Resistive Exercise Device (ARED), T2 Treadmill and the Teal ergometer [47]. Furthermore, the Flywheel cannot be used when Orion is docked to the Lunar Gateway due to insufficient vibration isolation. However, on the Lunar Gateway, albeit currently undefined ESA will provide and operate a Lunar Gateway Exercise Countermeasure Device – that will be significantly more capable than the Flywheel but again, potentially not equivalent to current ISS countermeasures [60] although a variety of optimisation approaches have been proposed [61]. Thus, exercise in µg prior to landing on the lunar surface may not entirely ameliorate deconditioning.

Apollo crew perfomed daily "Moonwalks" straight after 3 days in transit. Space adaptation syndrome, which includes disorientation was not reported in Apollo missions, which is surprising given its high prevalence in subsequent space programmes [33]. Nevertheless, Apollo crew stumbled and fell on the Lunar surface on several occasions, in particular when carrying a tools. Whilst, the specific cause of instability is unknown, locomotion style (i.e., "bunny hopping" [4], and/or skipping [31]) on the uneven Lunar regolith when donning Extra-Vehicular Activity (EVA) pressure suits are all likely factors.

In addition to the helmet that limited peripheral vision, the A7 EVA suits significantly restricted ankle, knee and hip mobility, compounded by the caudal and posterior displacement of the center of mass (CoM) due to the Portable Life Support System backpack [62]. In order to maintain balance crew presumably (as detailed assessment of gait biomechanics was impossible on the Lunar surface) tended to lean forward to counterbalance [22], increasing the risk of anterior-posterior, but also medio-lateral falls [67]. Restricted arm movement as well as inhibiting stability could also have contributed to the fact that having fallen, crew had great difficult in righting themselves leading to extreme stress (for the crew and mission control), elevated metabolic (and thus oxygen supply consumption), and ultimately exhaustion [66].

If more significant deconditioning is experienced in Artemis missions, a fall may become more likely, and potentially unrecoverable [15]. For instance, spinal adaptation [28], prime mover [23] and/or trunk muscle atrophy [11] combined with impaired proprioception [65] and motor coordination [64] may impair anticipatory postural adjustments [39] and postural resilience [16].

Whilst, prime movement atrophy may impair power generation required to getting back up. Furthermore, when falling there may be an increased risk of fracture [24] due to reduced skeletal integrity e.g., bone mineral density (BMD) and bone mineral content (BMC) [69], in addition to muscular or connective soft tissue injury [7], and the risk of prolapsed intra-vertebral discs which is a known risk post-flight [6].

Thus, µg and hypogravity-related deconditioning may present a significant risk to health and wellbeing, to task performance, and ultimately mission success. As a result, there is an urgent need to model the physiological deconditioning associated with exploration missions, to inform mission architecture including task definition, but also to determine the need for, and if so, definition of appropriate, and individualised exercise countermeasures.

6° Head down tilt bed rest (HDTBR) is the pre-eminent ground-based model of µg [30], although dry immersion [52] and hyper-buoyancy floatation [8] have been suggested to induce more rapidly and/or profoundly some of the adaptions associated with µg. As such NASA recently proposed that prior to crewed surface Artemis missions that a 30-day HDTBR study be performed at :envihab a German Aerospace Centre (DLR) facility in Cologne, followed by evaluation of EVA-related task performance. Whilst, such a campaign represents a "worst-case" case scenario – i.e., where crew perform no exercise prior to "landing" – it raises the question of how to define relevant tasks, to evaluate task performance (feasibility and functionality) in a way that informs the safety and success of future Lunar surface crew.

Fortunately adjacent to :envihab DLR and NASA have recently constructed a unique large-scale Lunar-surface analogue – termed LUNA – that will facilitate high-fidelity robotic and crew operations simulation [10]. LUNA will also incorporate a ceiling-mounted "Puppeteer" gravity offloading system that will be able to offload (to 0.16g) two crew moving in any direction simultaneously. In the summer of 2025, a free-standing (frame mounted) (linear) Puppeteer prototype will be trialled to inform the final system. Fortunately, despite the absence of Apollo biomechanical data – the key requirements for the "Puppeteer" system were derived from data collected as part of the Movement in Low Gravity (MoLo) programme instigated in 2014 by ESA in partnership with DLR and with several European academic institutions.

2 MoLo – preferred locomotion

The initial MoLo objectives were to evaluate hypogravity simulations and define "preferred" movement characteristics (unencumbered by an EVA suit) in "valid" simulated hypogravity in order to act as a baseline for novel surface EVA suit concepts, and to inform surface habitat design concepts. This work was required as gait velocity is known to be reduced by offloading (via prolongation of ground contact and flight times) [68] along with reductions in oxygen consumption (cost of transport) [53] and ground reaction forces [25]. However, gait velocity interacts with key biomechanical [27] and metabolic parameters [9] – presumably to optimise gait bioenergetics in a given context [45].

Furthermore, the picture is complex as substantial differences have been reported between methodologies [5]. In fact, the majority of simulated hypogravity studies have employed fixed speeds or standardised relative gait velocity [45] based on the resultant Froude number [1] – but leads to the question of how natural is the resultant locomotion. Furthermore, vertical offloading systems are frequently uncomfortable at the points of "offloading", in particular when unloading needs to be equivalent to 0.84g to simulate 0.16g leading to stilted gait, pain and poor participant compliance [9].

As a result, our initial studies employed the Vertical Treadmill Facility (VTF) to define preferred hypogravity walk, run (and walk-run transition) velocities along with subjective metrics across a range of simulated hypogravities including 0.16g. The VTF is a vertically-mounted treadmill where participants are suspended horizontally with a multi-point harness [17] and graded constant "pull-down", or return forces towards the treadmill belt are generated via pressurised cylinders [26] in a manner similar to the T2-treadmill on the ISS [18].

The application of 0.16g axial force on the VTF was deemed to be comfortable for short periods although it is unlikely to be as well tolerated as when similar loads are generated by a graded textile-based suits which have been worn for up to 8-hrs on earth and in space [63]. Furthermore, locomotion on the VTF is "unnatural" in the sense that the leg and arm body segments must be moved vertically with respect to the (1g) gravitational vector. Whilst participants reported that this was not a significant issue – the effect of this requires confirmation in a planned ISS technical demonstration that will compare preferred walk, run (and walk-run transition) velocities along with subjective metrics at 0.16g with the VTF on earth, and the T2 treadmill on the ISS in the same crewmember. Such data is key to inform Puppeteer definition and subsequent EVA (simulator) suit concept evaluations in LUNA.

3 LUNA facility

Whilst the LUNA facility is extremely high-fidelity in terms of regolith surface characteristics (EAC-1 simulant)[20] and light conditions via a specialized illumination simulator [10], these virtues render comprehensive marker (or even marker-less) multi-camera-based (motion-capture) assessment of EVA task functionality extremely challenging. Furthermore, the generation of airborne regolith is also likely to be highly problematic to subject-mounted instrumentation unless contained within the simulator suits. However, such instrumentation will be highly restricted as it is critical that it should not affect suit performance or general mobility. In addition, setup should be simple and robust without unduly extending testing and thus potential discomfort. Furthermore, it is anticipated that due to the multi-faceted nature of LUNA, high user demand will constrain facility access time.

As a consequence, the LUNA hall is not conducive for high-fidelity biomechanical (e.g., motion) analysis, nor high-volume testing needed for iterative task development and assessment. However, evaluations of candidate Lunar EVA tasks are critical to assess feasibility, suitability, and even potential injury risk prior to their use after a HDTBR-induced deconditioning – which is known to vary between individuals [59] complicating interpretation of its relationship to functionality even though basic task function is reduced by both HDTBR and spaceflight [41].

Definition of appropriate Artemis surface EVA tasks and subsequent understanding their functional requirements is challenging [13]. For instance, on Earth even small changes in seat height can significantly affect the biomechanics of rising in healthy individuals [35]. Indeed, simple task evaluation, task completion (and time-to-completion) data and subjective ratings are of limited value in supporting future Lunar surface task development. This is because failure, or high exertion scores do not demonstrate why someone had difficulty, nor directly indicate what are the factors that underlie the difficulty whilst providing little insight into whether another individual might have similar, or different issues. Therefore, comprehensive task-based motion analysis is critical to evaluate and help support task and/or training development.

4 MoLo programme

A "classical" comprehensive multi-camera motion analysis approach was taken by the most recent phase of the MoLo programme using the L.O.O.P (Locomotion On Other Planets) facility in Milano where we evaluated locomotion at variable g levels in addition to plyometrics (hopping, countermovement and maximal jumping) at variable g levels including lunar [32]. The L.O.O.P. facility provides high-fidelity hypogravity simulation via deployment of long

(17m) twin (in series) calibrated (via electric winch) bungee cords, where the relative change of bungee length, and hence recoil force is minimised during movement. This renders near-constant offloading that appears to be facilitate natural and fluid hypogravity movement.

In addition to derivation of 3D kinematics, an instrumented treadmill provided ground reaction forces (GRFs) that allowed the tracking of segmental and overall Centre of Mass (CoM; and its acceleration) with respect to Cente of pressure (COP) [32]. We consider this to be a key variable to evaluate the risk of instability during simulated hypogravity locomotion, and during plyometric motion. Plyometric jumping is being considered for inflight exercise – following amelioration of multisystem deconditioning in HDTBR [36] – with spring-based systems proving to be not only be feasible in µg [49], but with mass-balancing potentially implementable without requiring a vibration isolation system [12]. Furthermore, plyometrics is a candidate surface exercise modality with, or without a device [70], although in the latter prolonged flight times make CoM control (including "inflight" yaw rotation), and thus safe and controlled landings potentially difficult [29]. Having developed data pipelines to tracking this movement we hope to apply our approach to complex multi-directional body motion as will be performed in LUNA, and on the Lunar surface.

However, whilst CoM and movement kinematics characterise movement – it does not tell us about the "work" associated with the movement, nor the forces generated within, and exerted upon the body structures – key to understanding the demands (and risks) of a task. Indeed, vertical ground reaction forces (zGRFs) are considered to represent a key mechanical stimuli promoting "normal" lower limb musculoskeletal regulation. Indeed, on Earth zGRFs approximate 105% of an individual's body weight when walking, rising to almost 200% during running [19]. However, it is now thought that GRFs are complemented by other forces such as torsion [40], in addition to forces (loading, strain and strain rates) generated by muscles and propagated to the bone and across joints via muscle insertions / tendons [51]. Whilst complex, a multi-faceted relationship would be consistent with the strong association between "physical activity" and bone status in healthy individuals [44].

For instance, a reduction in forces acting through the Achilles Tendon may play a key role in the significant loss of BMD and BMC observed in the calcaneus [2]. Interestingly, we have demonstrated differential modulation of joint kinematics and contractile behaviour at simulated Lunar and Martian gravities [50]. Kinetics such as external work have also been shown to be reduced when walking, running and skipping at speeds representative of those observed (0.56 to 3.6 m/s) in simulated hypogravity [46, 45].

Furthermore, application of inverse dynamics from kinematic and kinetic data the forces and moments experienced at joints, muscles, muscle-tendons, and at the bone can be derived [21]. However, the relationship between external kinetics and internal forces requires computational musculoskeletal (MSK) modelling that represents local skeletal anatomy and relevant muscle-tendon unit physiology [54]. When combined with optimisation techniques, MSK modelling can yield estimates of muscle activation patterns (that can be verified with EMG) and internal kinetics, which are not currently measurable in vivo [3]]. Whilst this approach can distinguish between populations and exercise modalities [55] although it has only recently been applied to hypogravity simulation [42], including within the MoLo programme [14].

Applying optimisation framework modelling to L.O.O.P data hip, knee and ankle net joint moments were shown to decrease in proportion with simulated hypogravity during walking [5]. This approach has now been extended to simulated lunar gravity for walking, running, and jumping/hopping. The data processing is ongoing but novel data pipelines have been built to determine concurrent motion kinematics, CoM tracking in addition to the modelling of internal and external forces that can be used to determine the functional requirements of a given movement – scaled to an individual's anthropometrics.

5 MoLo-LUNA programme

Thus, we propose to leverage the kinematic, kinetic and MSK modeling approach developed for MoLo-Milano but extend it to evaluate tasks to be performed in LUNA in the forthcoming HDTBR studies. The initial step will be to optimise and run the multi- camera motion capture data pipelines for MoLo-Milano hopping and locomotion data (across 1g, 0.16g and 0.37g) to determine the effect of hypogravity upon CoM (with respect to base of support), internal and external work, MSK loading a during hopping and locomotion.

Then, by acquiring the free-standing Puppeteer prototype and housing it in a location in Cologne (termed MoLo-LUNA-LAB) we can comprehensively evaluate the conditions performed in L.O.O.P – which can support finalisation of the main Puppeteer system. Following this we propose to evaluate candidate EVA tasks prior to their performance post HDTBR. Continuing this work initially external to the LUNA simulation hall will allow completion of data collection in "shirt-sleave" mode to act as a baseline for subsequent suit-based evaluations. This would also allow the modelling pipelines to be optimised to support rapid task performance tracking and reporting coupled with complex (cloud-based) kinetics and MSK modelling.

Another key aspect that must be considered is the "functional delta" relating to the deconditioning expected at a given time in a mission. At present we have no defined valid way of evaluating functionality prior to missions. Furthermore, the deconditioning that may occur on the Lunar surface is entirely unknown. An approach to resolve this conundrum and to estimate expected deconditioning on the Lunar surface prior to Artemis missions is to determine the work (for aerobic fitness) and forces/loads required to perform defined activities in high-fidelity simulated hypogravity i.e., LUNA – and calculate the delta to that in 1g. By looping back to the individual tasks – via generation of a biomechanical digital twin [38] one can evaluate the predicted "functionality delta" for a given individual crew member which will vary according to many factors including size [58] and gender – with small females whilst potentially not as physically strong representing lower resource consumption [57]. This approach could be concurrent with digital twining to generate movement avatars within augmented/virtual reality [43] to promote real-time task performance [48] and training.

Furthermore, from the onset, the MoLo programme has sought to incorporate candidate "low-footprint", and thus potentially LUNA-compatible technologies/approaches. Several of these devices could be integrated into the simulator suit and form part of routine data capture as part of a "low-footprint" sensor matrix. However, such approaches must be validated with respect to an appropriate gold-standard methodology – i.e., multi-camera motion capture and demonstrated to be practical.

For instance, implementation of a single-camera approach is of substantial interest this is far more plausible in LUNA, in Lunar habitants, and even on the Lunar surface. In fact, single-camera approaches are increasingly being employed in professional sports – including by members of the MoLo consortium – based on standard camera video to not only track athletic performance but also to provide automated actionable insights for the coach.

This approach, if valid and applied to all LUNA EVA-simulation tasks, would facilitate the building of models that could determine the expected deconditioning for a defined mission architecture (vs. equivalent time period active in 1g), for a given individual. If one loops back to the functional requirements for a task, this approach can then be used to determine the "functional delta" between an individual at a specific point in a mission and the functionality they require for safe and effective completion of a given task.

Whilst these models are initially focused on EVA's modelling will need to consider that missions will evolve to include intermittent EVAs, and periods of habitat dwelling. Approaches such as those proposed in Lunar Life where intravehicular activity can be simulated in part by $+9.6^o$ Head Up Tilt Bed Rest (HUTBR) and Short arm centrifugation with 0.16g at the CoM [37]. However, Lunar habitats are also likely to involve elements such as stairs or ladders to access storage/sleeping areas, move between habitat levels, and potentially move between the habitant, and to the surface [29]. In fact, on Earth, stair climbing ability is considered a key risk factor for falls [34] and was a major concern for Apollo mission control. This highlights the need for the definition of optimal (or at least careful consideration of Lunar habitat ergonomics.

Finally, utilising a "low-footprint" sensor matrix in a way that is compatible with valid modelling on the Lunar surface enabling characterisation of activity vs. predicted capabilities to provide real time operational mission support, but also provide data to validate or optimise the deconditioning models built on earth. Thus, over time they could provide individualized functionality guidance to inform task performance, exercise definition, and prescription on the Lunar surface, but also potentially during transit and/or on the Lunar Gateway.

6 Conclusion

Thus, the MoLo-LUNA – leveraging the Molo programme – could become a key supporting activity for LUNA incl. validation of the Puppeteer offloading system itself via creation of a complementary MoLo-LUNA-LAB. Furthermore, the MoLo-LUNA programme could become a key facilitator of simulator suit instrumentation/definition, broader astronaut training activities and mission architecture development. By employing a Puppeteer system external to the LUNA chamber hall it will optimise utilisation and cost-effectiveness of LUNA, and as such represents a critical service to future LUNA stakeholders. Furthermore, MoLo-LUNA would generate a unique data set that can be leveraged to predict de-conditioning on the Lunar surface – and thereby optimise functionality, and minimise mission risk – including informing the need for, and prescription of exercise countermeasures on the Lunar surface, and in transit. Thus, MoLo-LUNA offers a unique opportunity to place LUNA, and ESA as a key ongoing provider of evidence to define, optimise and support crew Artemis surface missions.

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Assessing the Use of Mixed Reality as a Valid Tool for Human-Robot Interaction Studies in the Context of Space Exploration

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Abstract

Mixed Reality (MR) is a technology with strong potential for advancing research in Human-Robot Interaction (HRI) for space exploration. Apart from the efficiency and high flexibility MR can offer, we argue that its benefits for HRI research in space contexts lies particularly in its ability to aid human-in-the-loop development, offer realistic hybrid simulations, and foster broader participation in HRI research in the space exploration context. However, we believe that this is only plausible if MR-based simulations can yield comparable results to fully physical approaches in human-centred studies. In this position paper, we highlight several arguments in favour of MR as a tool for space HRI research, while emphasising the importance of the open question regarding its scientific validity. We believe MR could become a central tool for preparing for future human-robotic space exploration missions and significantly diversify research in this domain.

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1 Introduction

Robotic systems can be considered essential for space and planetary exploration, maintenance of space stations, and autonomous operations in deep space. For space missions involving humans, efficient collaboration between humans and robotic systems is vital to mission success [14, 18]. Consequently, human-robot interaction (HRI) studies are carried out to gain knowledge about the interaction between humans and robots. Conducting HRI studies is challenging for multiple reasons: First, the availability of the robot is limited, as the development of robotic systems for space missions might not be finished at the time the study is needed. This creates a "chicken-and-egg" dilemma: HRI study results are crucial for robot design, yet a robot is often prerequisite for comprehensive studies. Second, testing robotic systems in space is unfeasible, necessitating their evaluation in simulated or artificial environments.


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Indeed, this problem has been extensively explored in Human-Computer Interaction (HCI) research, particularly through the study and use of various speculative design methodologies, including speculative enactments [11] and design fiction [27]. Mixed reality (MR) technologies, however, offer a powerful approach in addition to these existing speculative approaches. By enabling HRI studies with highly interactive and immersive virtual robot prototypes in blended real-virtual spaces, MR allows participants to engage in situated, embodied interactions that were previously difficult to achieve without physical hardware. According to the reality-virtuality continuum of Milgram [31], we understand MR as all variations of technologies that can merge real and virtual objects in the view of a user, including but not limiting the scope to the most prominent variant of augmented reality (AR).

While MR offers enormous potential in HRI research, there is still limited knowledge about the validity of using simulated robots in HRI studies. However, our ongoing work particularly researching the validity of HRI studies with virtual robots indicates that MR studies produce almost identical results to studies done with real robots. Based on this experience we argue that MR studies are a feasible alternative to HRI studies with real robots.

In this position paper, we argue that MR should be more widely used in HRI studies in the context of space exploration. Here, we first provide information on the established methods of HRI studies in the spaceflight domain in Section 2. Based on this, we highlight the potential of MR in Section 3. In Section 4, we summarise the current state of research in terms of validity of HRI studies including our own work that indicates that MR studies are valid, before we conclude the position paper in Section 5.

2 Established Methods in the Spaceflight Domain

To understand the methodological gap that MR could address, it seems helpful to review current approaches used to evaluate human-system and human-robot interactions in the context of space exploration. A common approach has been the use of so-called *analogue missions*. These missions replicate certain conditions found on planetary bodies such as the Moon or Mars [32]. This replication is achieved by conducting missions at locations on Earth that have specific similarities to extraterrestrial environments, such as the lunar surface. Analogue missions can be seen as essential means for performing tests on aspects regarding scientific, technological, and operational challenges of planned space missions [39]. This includes investigating specific human-centred questions and challenges such as insights into efficient astronaut-robot interactions techniques for surface operations [5]. While these analogue missions are seen as instrumental, they are rarely designed with systematic HRI research in mind. Academic studies explicitly investigating astronaut-robot interaction in such environments remain scarce, and the existing efforts are mostly driven by space agencies with a focus on engineering evaluation or mission preparation [18].

As much as these analogue campaigns are critical to prepare for future human-robotic exploration mission on extraterrestrial surfaces, they also come with some notable challenges. They require extensive planning and coordination, often involving complex logistics due to their remote and harsh locations. These sites–such as the Barringer Crater in Arizona [5] or the volcanic terrains in Spain and Italy [41]–are chosen for their similarity to extraterrestrial surfaces, but can be rather difficult to access and operate in. Alternatively, analogue facilities and lab-based physical simulations offer more accessible alternatives to remote analogue missions. Analogue facilities, such as ESA's LUNA [12] or neutral buoyancy facilities [33], replicate extraterrestrial conditions in controlled environments and can be used more flexibly

and frequently. Similarly, high-fidelity physical tests conducted in laboratory settings can simulate planetary operations without requiring complex field deployments [14]. Even with these approaches, however, scientific HRI studies remain scarce. The existing body of HRI research in the space domain appears rather minimal and fragmented [37]; partly perhaps due to the aforementioned institutional context of these initiatives, which are often led by space agencies with operational rather than academic goals.

In recent years, however, Virtual Reality (VR) has increasingly been proposed as an additional helpful tool [7, 38, 10]. When designed effectively, VR-based simulations provide a cost-effective, flexible, and highly accessible alternative to analogue sites, facilities, or entirely physical lab-based test scenarios. Due to these aspects of VR, it can be used for better design evaluations [36], evaluations of concepts of operation [10], or the familiarisation of astronauts with robotic devices on the International Space Station (ISS) [7]. However, this approach comes with trade-offs, as certain aspects of realism are inevitably reduced–even when the virtual environment is meticulously crafted. In particular, tactile elements such as realistic haptic feedback, as well as the physicality required for natural interaction, remain difficult to reproduce in fully virtual settings.

In contrast, we argue that MR can offer a compelling middle ground, combining the flexibility and accessibility of virtual simulations with the physical realism, situational context, and physical fidelity of real-world test scenarios. In some cases, it may even enhance these aspects further by adding contextual realism or environmental augmentation. Some researchers in the field of HRI even suggest that interactions with virtual robots presented through AR could yield results similar to interactions with physical robots [19, 25, 16, 30].

3 The Potentials of Mixed Reality

This section provides an overview of why MR presents a highly beneficial technology for HRI in the research domain of space exploration. We first provide an overall look at the general advantages immersive, or Extended Reality, technologies can provide, before focusing on key benefits that are specific to HRI in space-related HRI scenarios.

3.1 General Benefits: Enhancing Efficiency and User-Centric Design

Immersive technologies such as VR and AR provide significant cost-efficiency advantages by enabling simulation and virtual prototyping throughout the design process [8, 24]. Instead of investing in multiple physical prototypes, engineers can develop and test virtual models. These digital iterations not only streamline the development cycle but also drastically reduce both material expenses and labour costs [8, 24, 4, 28].

Moreover, the iterative nature of digital prototyping allows for the early involvement of end-users. Usability and user experience tests can be conducted in the initial stages of development, even when the physical hardware does not exist yet. This early feedback loop facilitates the rapid identification and elimination of potential design flaws, thereby reducing the risk of costly errors later in the project timeline [6, 15]. While this might theoretically be also possible with desktop simulations, MR offers a distinct advantage in HRI contexts through higher immersion and more natural, embodied interactions. For example, instead of exploring a 3D rover model with a mouse and keyboard, MR allows users to physically engage with an augmented rover chassis, potentially using their hands for more intuitive control. This direct, physical interaction within a blended real-virtual space yields unique insights into spatial understanding and user experience, which can be pivotal for HRI research and justify

the adoption of MR. Research suggests that user studies conducted with immersive virtual prototypes yield results that are comparable to those obtained using physical prototypes, validating the effectiveness of these digital approaches [8, 21].

Another considerable advantage of early virtual prototyping is its role in end-user training. As soon as the design phase is complete, virtual systems can be deployed to train users–even if the final physical systems are not yet available. This ensures that personnel are well-prepared and familiar with the system, reducing the learning curve when the physical hardware is eventually introduced. Additionally, the ability to simulate operational scenarios in virtual environments provides a safe and cost-effective platform for testing the system's performance in dangerous, remote, or expensive-to-replicate conditions [13]. Users can gain valuable experience in decision-making during high-risk scenarios, thereby enhancing overall mission readiness and system reliability [20].

In summary, immersive technologies not only reduce development costs and time but also improve the overall quality and safety of system design through early user involvement and flexible training environments. While these mentioned aspects apply broadly to many domains, the following section focuses specifically on the unique potential of MR for HRI in the context of space exploration.

3.2 Specific Benefits of Mixed Reality in the Human Spaceflight Domain

Several key benefits for HRI in space exploration stem from the fundamental capability of MR of combining virtual and real-world elements into a shared interactive space. The following are some of the most pertinent and encouraging advantages of MR, in our opinion as HRI researchers. While this is not an exhaustive list, it outlines key affordances that could meaningfully enhance how HRI is studied and designed in space-related domains with the help of MR.

3.2.1 Human-in-the-Loop: Enhancing HRI in Hybrid Robotic Systems

One of the major benefits of MR which is particularly relevant for HRI is its ability to facilitate interaction with virtual or partially virtual robotic systems. While VR can also simulate such interaction (only the fully virtual ones, however), the combination with real-world context sets MR apart. It not only enables safe yet potentially more natural interaction with a virtual robot compared to fully immersive VR environments; it also allows for the augmentation of physical robotic components [40].

For instance, a physical (maybe even low-fidelity) rover chassis might be enriched with a virtual manipulator or scientific instruments. Multiple variations of these virtual components could then be tested using an experimental setting following a between- or within-subjects design. This allows researchers to test and iterate robotic designs with human input and interaction well before the physical hardware is finalised. MR thus enables early human-in-the-loop development of robotic systems intended for future missions, helping to integrate human-centred design principles from the very beginning. That would also allow for early testing of astronaut-robot interaction techniques, workflows, or task protocols.

A limitation that can be pointed out in this regard could be that the interaction with, for example, a virtual manipulator of a rover would still be virtual; thus there would be a lack of haptic feedback or tactile aspects (during a handover for example) that would differ from the experience one would have when utilizing physical components. However, MR's ability to merge the physical and the virtual leaves it up to the experimenter where a tangible interface is needed and where a virtual one may suffice.

3.2.2 Realistic Hybrid Environment Simulations

Another major strength of MR that we see is the ability to carry out virtual HRI simulations within a realistic physical context. Real-world conditions such as lighting conditions, acoustics or various environmental details are therefore already available without having to be reproduced in a completely virtual environment. This can be particularly relevant for analogue facilities such as LUNA, where the physical setting can be preserved while being enriched with virtual content. In this way, the realism of the physical environment is preserved, while simultaneously benefiting from the flexibility of a virtual simulation.

That way, MR enables the creation of hybrid test beds that blend physical analogue environments with virtual additions. Such environments can offer the potential to approximate lunar surface conditions and mission scenarios in ways that would be difficult, or outright impossible, to achieve with physical means alone on Earth. Examples include the behaviour of passive objects under lunar gravity, which are not directly interacted with but still shape the environmental context [35]; challenging lighting conditions such as deep, sharply defined shadows cast on the Moon's surface [35]; the simulation of lunar dust behaviour, including how dust clouds form, move, and settle on equipment and surfaces; or the addition of a distant lunar horizon, which can evoke a greater sense of spatial scale and immersion.

As previously mentioned, recreating such conditions physically would be prohibitively complex or entirely unfeasible. MR thus provides a valuable opportunity to incorporate these otherwise inaccessible features into HRI research scenarios, paving the way for exploring and evaluating mission-critical factors under more realistic conditions for space missions.

3.2.3 Broader Accessibility and Flexible Simulation Setups with Adaptable Levels of Virtuality

By supporting simulations in physical, and therefore often more realistic, environments, and by allowing for the augmentation of physical elements with virtual content, AR holds considerable potential for increasing the accessibility of HRI research in the human spaceflight domain to a broader range of institutions and researchers. As MR and AR offers the ability to dynamically add virtual elements to physical objects [17] and therefore potentially adding details to the objects, institutes and research groups could enhance low-fidelity physical mock-ups or basic robotic systems with virtual elements. This can enable them to study partial aspects of future mission scenarios without full-scale hardware. While VR could support a similar notion, its limitation lies in largely omitting these aforementioned physical aspects.

Importantly, MR allows for more flexibility in simulation setups: researchers can decide which components should be physical and which virtual, depending on the development stage and the specific aspects of interaction being studied. This adaptability is further supported by emerging technologies and, at the time of writing this paper, the most cutting-edge devices such as the Apple Vision Pro [3], Meta Quest 3 [29], or Varjo XR-4 [42], which allow for dynamically adjusting the degree of virtuality. Such technologies can enable hybrid laboratory setups in which certain elements are physically present while others are virtual. They also allow for enhancing physical lab environments with additional visual context, such as features of the lunar or Martian surface, without fully abandoning physical interaction, as would be the case in VR.

Establishing such hybrid lab settings would, from our point of view, foster greater participation in HRI research targeting the human spaceflight domain. Such increased participation would allow, as already suggested in the earlier specific aspects of future human-

robot exploration missions on the Moon or Mars to be examined in greater depth by domain experts. This includes factors that may significantly influence the quality of interaction between humans and robots–both positively and negatively–such as trust, usability, mental workload, cognitive fatigue, or acceptance.

4 The Question of Validity

While the previously outlined aspects of mixed reality may indeed offer significant value, we believe this potential is largely contingent on one critical condition: MR studies, experiments, and test scenarios must yield the same–or at least comparable–results as fully physical scenarios with physical robots or even in real operational contexts. This raises the fundamental question of *ecological validity*, which, in this context, means if the results of an HRI study done in MR would be similar to those from a real-world situation involving a physical robot [9].

4.1 Empirical Perspective

Previous research has correctly identified the most straightforward way of investigating this question: by conducting identical studies with real robots and with simulated robots. Interestingly, most comparative studies carry out their experiments using VR-simulated robots, such as Nenna et al. [34] investigating mental workload during a pick-and-place task; Li et al. [26] and Kamide et al. [23] comparing general human perception in regards to the proximity of an operating robot or Villani et al. [43] mainly investigating mental workload during a human-robot navigation task.

To our knowledge, the only two empirical comparative studies using physical and AR-simulated robot are the ones by Han et al. [19] and Mielke et al. [30]. Han et al. compared physical and AR-based robot gestures and found no significant differences in accuracy, anthropomorphism, or social attributes such as likeability, warmth, and perceived competence. Mielke et al., on the other hand, showed that human-robot tasks like pick-and-place scenarios can yield comparable results between real and virtualized setups in regards to workload and task ease.

We as a research group have set ourselves the goal to investigate the question of valid AR simulations in HRI, too. For this purpose, we conducted two identical experiments that investigated human trust in industrial robots. One of the experiments used a physical robot [2] and one used an AR-simulated robot [1] in a real environment. From these two studies, early insights can be drawn. In the studies, a human and a robot carried out collaborative handover tasks in the context of industrial disassembly of hazardous components. We measured the perception of trust, predictability, faith, dependability, safety, and adaptability multiple times during the studies, resulting in 98 data points to be compared. A statistical comparisons showed no significant differences between the physical and the AR condition for most of the data points measured. However, a small number of the data points showed significant differences, which might be attributed to situations, in which a robot fails in executing a physical task (in the study, differences showed in the variable trust, when the robot failed to remove a rusty screw). The results were all based on non-parametric Mann-Whitney-U tests at a significance level of $\alpha = 0.05$.

While this shows that interaction with AR simulated robots may indeed yield similar results as interactions with physical robots and can therefore provide ecological validity, the question may remain how these indications can be transferred to human space exploration.

4.2 Implications for Space Exploration

While previous results from MR-based HRI studies indicate that virtual simulations can deliver valid results, the transferability of these findings to the space exploration context is anything but self-evident. Space missions involve very specific environmental conditions, work requirements, and psychological stress that differ greatly from typical laboratory scenarios. This raises the question of how ecological validity can be meaningfully assured or at least approximated in the field of space research.

We see two potential complementary approaches to address this challenge and to try to better understand the question of validity of MR-based HRI studies in the context of spaceflight:

(1) General lab studies as indicators: Studies such as the ones that have been described in Section 4.1, will likely emerge in a higher frequency in the future. These studies, that happen in classic lab settings with a fully physical counterparts that can be feasible to make identical to the MR-simulated condition, can be initial indicators for validity. The more variety these studies show (concerning different interaction techniques or dependent variables), the clearer the picture becomes. Regarding important variables in the HRI context like workload, performance, or trust, such empirical research can deliver valuable insights for astronaut-robot interaction, thus providing a degree of plausibility of MR-based research. Nevertheless, such findings should be interpreted with caution, as typical HRI scenarios in space exploration are significantly more complex and context-dependent.

(2) Comparative studies with a focus on space exploration: A more targeted approach involves designing MR-enhanced HRI lab studies that resemble conditions and tasks relevant to space exploration. For instance, experiments could compare the interaction with a low-fidelity physical robotic mock-up augmented with virtual elements to the interaction with fully physical robotic systems, while carrying out a scenario relevant human-robot activities on the lunar surface such as scouting and exploration, cooperative construction activities, or even emergency assistance scenarios [22]. Additionally, the influence of a virtualised environment–for example, a simulated lunar surface–could be evaluated against physically reconstructed analogues like ESA's LUNA facility. While such studies are more complex to design and execute, we believe that they offer the most promise for shedding light on the validity of MR in human-centred space research. Moreover, they may approximate the transferability of MR findings to real-world space missions.

Combining both approaches can provide a stronger foundation for understanding and investigating the ecological validity of MR in space-related HRI research. Moreover, this direction may help open the door to a broader participation in space research, allowing more institutions to engage in realistic HRI simulation and design efforts without needing access to physical hardware or analogue mission infrastructure.

5 Conclusion

Mixed Reality holds substantial promise for advancing HRI research in the context of space exploration. By enabling hybrid simulations that combine physical realism with virtual flexibility, MR allows for early-stage testing, human-in-the-loop evaluations of robotic systems, and potentially broader participation in HRI research in the spaceflight domain.

However, we believe that this potential is only fully realised if MR-based studies can yield comparable results to those obtained through more established, physical experiments. In this paper, we argue that this scientific validity is essential for establishing MR as a reliable tool for space-related HRI research.

Thus, the future utility of MR in HRI research in the context of space exploration hinges on its demonstrated, ecological validity. This requires systematic comparative studies in which MR-based interactions are directly evaluated against their physical counterparts. Such comparisons should ideally be carried out in scenarios specific to space exploration. However, comparative studies in general HRI context could deliver valuable implications for space exploration-related scenarios, too. Key variables like trust, workload, and human-robot performance should then be empirically examined. If pursued rigorously, this line of research could establish MR as a scientifically validated and broadly accessible tool for astronaut-robot interaction and, as a long-term perspective, enabling deeper insights into human-centred space mission design by making the participation more inclusive.

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Underwater VR for Astronaut Training

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Abstract

Pools are excellent places for testing many nautical technologies, as well as training divers or astronauts in simulated weightlessness. However, for extensive astronaut training underwater, a large pool is necessary. The Neutral Buoyancy Laboratory (NBL) is an astronaut training facility and located at the Sonny Carter Training Facility, near the Johnson Space Center in Houston, Texas, containing 23 million liters of water. In Europe, Blue Abyss Ltd. is currently building the world's largest and deepest indoor pool in Cornwall, also having space applications in mind. We believe that a VR solution can overcome the needs for large pools for astronaut training as space equipment can be well-simulated in virtual reality. To this end, we combined a full-face diving mask with a custom built VR headset for simulating a space environment. Besides constructing a water-tight VR headset, a precise tracking system to determine the position and orientation in space plays an important role. We use an outside-in tracking system consisting of four cameras in watertight housings, mounted on aluminium rails, covering a 2×3.5 meter experimental area, which enable us to track reference markers placed on the underwater VR diving mask. To calibrate this system, a rectangular cuboidal structure with reference markers is placed in the experimental area, which additionally serves as a handrail to perform basic Extra Vehicular Activity (EVA) tasks. The position tracking of the underwater headset and mirroring of physical objects in VR enables the user to move physically in the virtual environment as well as interact with the physical objects, such as the handrail. Due to the underwater environment, refraction at different media needs to be taken into account for both calibration and tracking.

2012 ACM Subject Classification Human-centered computing → Empirical studies in visualization; Human-centered computing → Visualization theory, concepts and paradigms

Keywords and phrases Head Mounted Display, VR Glasses, Underwater, Motion Tracking

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Supplementary Material *Audiovisual (video demonstrating the approach)*: `https://youtu.be/rKG1XqJKrDw` [6]

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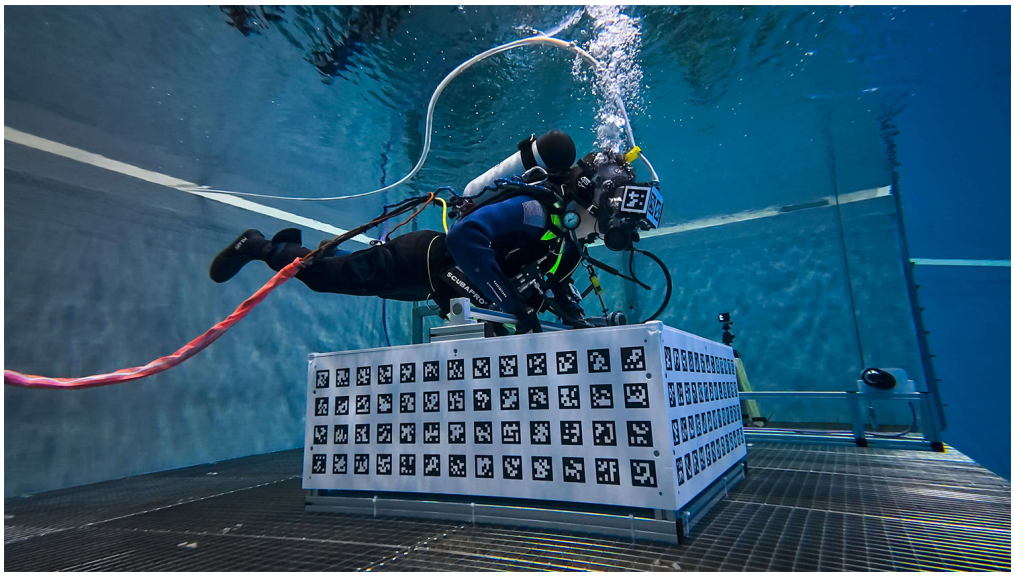

Figure 1 Astronaut Matthias Maurer testing the VR headset at ESA's Neutral Buoyancy Facility.

1 Introduction

"Diving is the poor man's spacewalk", a saying frequently used by diving instructors in their beginner courses just before students take their first plunge underwater. The European Space Agency (ESA) states on its homepage that "Training underwater is as close as it gets to experiencing weightlessness on Earth so spending time in a full spacesuit is used to practise techniques for spacewalks and neutral buoyancy is substituted for microgravity." [2].

The world's largest indoor swimming pool is NASA's Neutral Buoyancy Laboratory (NBL) in Houston, Texas, boasting a capacity of over 23 million liters of water. However, even with dimensions of 62×31×12 meter, it's still not large enough to house a complete model of the International Space Station (ISS). Instead, specific modules are swapped in and out as needed. In Cologne, Germany, the European Space Agency (ESA) operates the Neutral Buoyancy Facility (NBF), an octagonal-shaped indoor pool measuring 22×17×10 meter and holding 3.7 million liter of water. Despite their immense utility for astronaut training, the operation and maintenance of such facilities is a complex and expensive endeavour.

Virtual Reality (VR) involves simulating a virtual environment, projecting it onto 3D near-eye displays, and adjusting the view based on system movements to fully immerse the user. VR has gained significant popularity, especially within the gaming industry, following the launch of the Oculus Rift in 2012 and Facebook's subsequent acquisition of Oculus VR in 2014. Nowadays, VR is utilized in various applications, such as entertainment for gaming, movies, and concert streams, in education for training professionals before undertaking difficult tasks (e.g., fire-fighting, mining or medical operations), and in archaeology to preserve heritage sites for future generations.

This works demonstrates that an underwater VR system serves very-well as a viable alternative to current astronaut training methods, offering the advantage of simulating large structures like the ISS in a small pool. This paper begins by providing background information on the decisions made during this endeavour, followed by a detailed description of the current system, a presentation of initial tests conducted, and concludes with an outline for future work.

2 Background

When developing an underwater VR system, one has to face certain challenges. Commercial VR headsets are meant to be used in air, which means they are not waterproof. Additionally, proprietary hard- and software is used, so accessing certain elements such as the sensors or image stream is not possible. When looking for off-the-shelve underwater VR headsets, the DIVR by Ballast VR [11] comes to mind. This is a watertight, cordless VR system, meant to be used in aquatic entertainment. They provide different virtual environments, and the system is meant to be used e.g. in water slides or while just snorkelling in a regular pool. Additionally, they offer a stationary thruster system, which emits fluctuating thrusts of water. However, the same as with classical VR headsets, neither the hardware nor sensors are accessible. Also, though named DIVR, the system is only certified of submersion up to 1.2 meters. Therefore, the decision was made to build a custom VR headset from scratch.

One of the most important aspects of virtual reality is the movement tracking of the head in order to adjust the projected images accordingly. On the other hand, the movements of real objects, e.g., tools, in the workspace should possibly also be tracked in order to be able to interact. In all cases, very high precision, update rate, and range of position measurements are critical. Tracking systems use a wide variety of technologies to determine the position in space. These include measurements via ultrasound, laser, mechanical coupling, gyroscopes, image processing systems, or hybrid systems. Independent of the chosen physical measurement method, a further distinction can be made between the position of the sensors and the reference to be measured, i.e., auxiliary objects (so-called beacons or markers) that are used for the actual position determination. These systems are categorized as either inside-out or outside-in tracking based on how they determine the position and orientation of the user's head in relation to their surroundings. Inside-out tracking typically uses camera sensors to track feature points in the environment in combination with inertial sensors to estimate the head pose with respect to the environment. This requires integrating the camera sensors into the underwater headset, which makes the diving mask bulky and the setup more difficult for prototyping. Therefore, we opted for an outside-in tracking system based on four FLIR BFS-PGE-23S3C-C industrial cameras [3]. The tracking in work is achieved by marker detection via a set of four cameras, which are integrated in watertight housings and permanently submerged.

3 Hardware Setup

3.1 The VR Headset

Building a budget VR headset from scratch is something, that, ever since Google launched the well-known, but now discontinued Cardboard [4] in 2014, has been the playground for many Makers around the world. As a starting point for this work, the open-source project Relativty [9] was chosen, since the recommended displays offer 2 K resolution at 120 Hz and the kit includes a Mobile Industry Processor Interface (MIPI) to Mini Display Port (mDP) controller board, which is powered using Micro USB, while being still affordable with around 200 USD. To test the basic functionality, a small mock-up was designed and 3D printed, cf. Fig. 2. Two Fresnel lenses with a focal length of 50 mm are mounted on a sliding mechanism, in order to adjust for different interpupillary distances and visual acuities. The displays are connected via the controller board to a desktop PC. This mock-up was used to provide an easy and simple handheld device to work on the virtual environment and the tracking, as described in the next two sections, while adapting the VR headset onto a diving mask.



Figure 2 Left and middle: 3D printed mock-up for testing the displays and lenses. Right: 3D printed housing for the Interspiro Divator Full Face Mask.

The diving mask chosen is the Interspiro Divator Full Face Mask [5], due to it being widely spread amongst professional divers, as well as being used by the European Space Agency (ESA) for their underwater astronaut training. The design consists of six different parts, shown in Fig. 2. The first part in dark grey on the right is specifically modelled to fit onto the shape of the Divator visor. It is glued onto the mask and sealed off with a waterproof silicone to fill all remaining gaps between the visor and the part. Next, shown in light grey, is a laser-cut 2 mm silicone gasket. The part in medium grey is a mounting plate for the displays, which is screwed onto the left part, again in dark grey, that contains the controller board and an outlet for the power and display cables. The casing is bolted together with 16 stainless steel screws and nuts, and 32 stainless steel washers to redistribute the clamping force. The two black parts show in Fig.2 are attachment plates for reference markers. To safely guide the power and display cables to the surface, a 22 mm silicone tube is clamped to the cable outlet. One of the biggest challenges of underwater VR is water tightness. Therefore, the whole casing in rev1 was 3D printed with 100 % infill using a FDM (fused deposition modeling) printing. Additionally, any grooves on the connecting surfaces touching the silicone gasket are filled with a waterproof epoxy, sanded down, spray coated, and again sanded down for maximum smoothness. In rev2 resin printing, also known as SLA (stereolithography) has been used. Rev3 was made all-alluminium using milling. Here we have replaced the silicone gasket with an O-ring.

Since all electronics are enclosed and bolted down in the watertight housing and adjusting the lens-to-lens and lens-to-screen distances would be tedious if integrated within the housing, they needed to be mounted inside the mask itself. The Interspiro Spectacle Kit is a solution by Interspiro to use custom lenses with a diving mask. It comes with a mounting frame, which is put inside the mask, and a lens holder, which attaches to the mounting frame via an up-and-down-slideable rubber piece. Since the lens holder is angled and does not accept sound lenses, a custom lens holder was designed and 3D printed to accommodate the Fresnel lenses. To adjust for different interpupillary distances, multiple pieces with 60 mm to 65 mm center-to-center distance are available. To adjust for different visual acuities, the connecting pins are 8 mm long. Also, the lens holder is designed such that the lenses are mounted parallel to the displays. The mounting frame and the lens holder are shown in Fig. 3. The complete VR diving mask is shown in Fig. 3. The connected cables are an optical mDP to DP cable and a Micro-USB Cable, both 10m long, to accommodate for diving depths of 3 m in a 3×3 m pool while providing enough length to connect to a PC, located next to the pool.

3.2 The Virtual Environment

The two scenes shown in Fig. 4 are implemented in the Unity game engine. To create the necessary output stream for the VR headset, a dummy body with two cameras with an interpupillary distance of 60 mm as ”eyes”. The video stream sent to the VR headset has a resolution of 2880×1440 pixels, split vertically into two equal parts for the left and right eye.

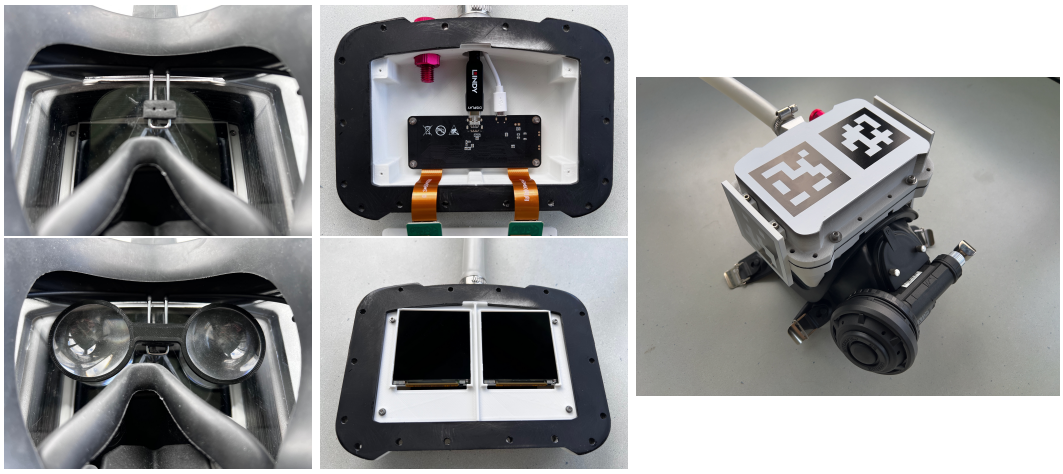

Figure 3 Left: Mounting frame (above) for lens holder (below). Middle: Controller board with cables inside the housing (above), displays and mounting plate (below). Right: Full assembly on the Divator diving mask with tracking markers.

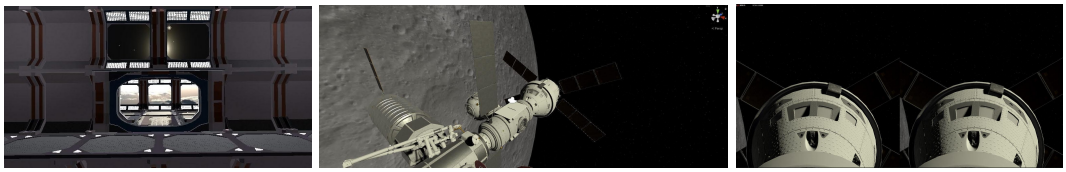

Figure 4 The Virtual Environment. Inside an artificial space station (left), an outside view of a Lunar Gateway Mock-up (middle) and a view projected onto the VR headsets (right).

One of the goals defined by ESA was to have the Lunar Gateway Space Station as the central objective in the modeled game environment. As there already exist numerous 3D models on the Internet under open licenses, one of these models was selected to be utilized for this project. The chosen model[1] provides Unity Universal Render Pipeline (URP) files to embed it directly into Unity. The exact dimensions and positions of the objects in relation to each other have been preserved in Unity, so they match the dimensions of the real objects.

3.3 The Tracking System

Head tracking systems are used in various applications, including virtual reality (VR), augmented reality (AR) and human-computer interaction, to estimate the movement of a user's head. In our setup, four cameras are placed on opposite sites around the workspace on aluminium bars with a camera-to-camera distance of about 1.8 m and a bar-to-bar distance of about 3.4 m. On the underwater headset, AprilTag [8] fiducial markers are fixed to allow 6-DoF tracking of the head pose if at least one marker is visible. The cameras are mounted approximately 0.3 m above the ground, tilted inwards by 30 ° and upwards by 15 ° to ensure good coverage of the workspace. A schematic overview of the setup is shown in Fig. 5, top.

The cameras are integrated into underwater housings with acrylic viewports and are connected via Ethernet to a computer outside the pool for image processing and motion estimation. In water the viewport acts like an optical element. Due to the change in refractive

[1] https://www.artstation.com/marketplace/p/5j9Jv/gateway?utm_source=artstation&utm_medium=referral&utm_campaign=homepage&utm_term=marketplace

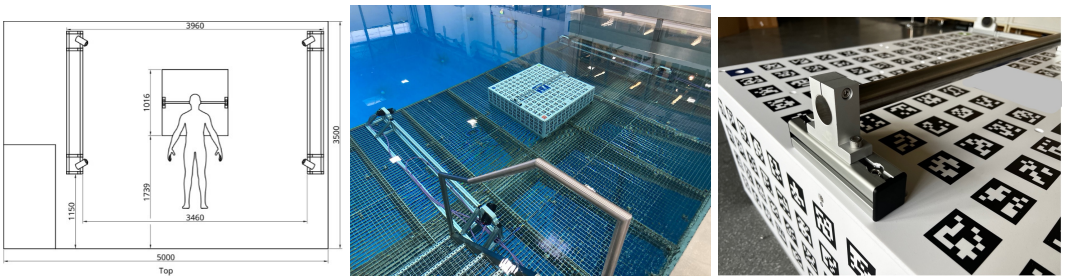

Figure 5 Tracking Setup as a Top-Down-Sketch with dimensions and a dummy body (left), the setup inside the pool (middle) and a closer look at the center structure and handrail (right).

index between water, glass and air, refraction occurs. In order to minimize the effect of refraction, dome ports are employed. Dome ports are built from a hemispherical glass shell and aim to minimize the geometric changes of the light path. If the camera center is aligned with the center of the dome port, the ray from the object through the center of projection to the image point is perpendicular to the spherical media interfaces. Therefore, no refraction occurs, and a near-perfect central projection is provided. The advantage of the dome port is that the field of view and image distortions are unchanged if the camera is centered. However, the depth of field increases slightly, and the focus distance is different compared to air. The spherical interface acts similarly to a negative lens element. Hence, the objects captured through the dome port appear to be closer.

Examples of a dome port and flat port underwater housing are shown in Fig. 6. The top left image shows a dome port housing that is rated for a depth of 750 m. The flat port housing depicted in the top right images features a 19mm thick glass window and a depth rating of 1750 m. In the two housings, two industrial machine vision cameras are integrated. Below the housings, example images of the two underwater cameras are shown. The images are captured with the dome port and flat port partially submerged in water.

The top half of the images is in air, while the lower half is in water. The dome port image shows little geometric distortion of the captured chessboard, which suggests that the camera is well-centered in the hemispherical glass window. The sharpness of the image is noticeably different for the part of the image in air and water since the camera needs to be focused at different distances. Here, the camera-lens system was focused for the in-water conditions. The bottom right image visualizes the different magnifications of the flat port interface in air and in water. The chessboard appears closer in the lower half of the image captured in water. The magnification and focal length of the combined camera and housing system are increased.

We align the camera based on the manufacturers specification of the position of the entrance pupil of the lens. Smaller errors in alignment are compensated by in-situ camera calibration [1]. We do not apply a specific underwater camera model but assume that the errors are absorbed by the radial and tangential distortion model. The cameras are individually calibrated in water using a calibration board. The extrinsic parameters of the cameras are estimated online using AprilTag markers placed on a fixed structure in the center of the workspace. This way, the setup can be easily reconfigured without performing re-calibration. The cameras are synchronously triggered and deliver an image stream with up to 80 Hz. For each image set, the head pose is computed by minimizing the reprojection errors of the projection of all visible AprilTag marker corners on the individual camera sensors. After head pose estimation, filtering is applied to smooth the pose output and avoid erroneous fast movements due to tracking failure, which would negatively affect the user.



Figure 6 Dome port (above left) and flat port (above right) underwater camera. Below are two example images with the dome port (below left) and flat port (below right) partially submerged in water. The top half of the image is in air while the bottom half is in water.

All structures are build from aluminium bars with aluminium and stainless steel connectors, the cameras are mounted with 3D-printed attachments made from PET. The center piece is a 1×1×0.42 m cubic shaped structure. 8 mm PVC foam boards with printed on makers are mounted on all four sides and the top. On top of the structure, a 30 mm diameter aluminium rod is mounted about 0.5 m above ground and acts as a handrail to perform basic EVA movements.

The data processing of the camera streams runs on a dedicated workstation PC (i9-13900KS, 64 GB RAM). All cameras are connected to a 10 GBit/s Switch, to allow for the simultaneous transfer of four 2.3 MP video streams at up to 80 Hz. The data processing is done with the Robot Operating System (ROS) [10, 7], which provides the pose of the tracked headset via a ROS-to-Unity bridge. The Unity simulation listens to the data processing for updates on the current headset pose and moves the virtual cameras accordingly.

For the final version of the headset, i.e., rev3 as described above, an inertial sensor is used in addition to optical tracking, which is also integrated into the headset. For this purpose, the BNO085 IMU breakout board from Adafruit was selected, which is equipped with the BNO085 inertial measurement unit from CEVA Technologies, Inc. The sensor employs the same hardware as the Bosch Sensortech BNO055, but with an optimized firmware specifically designed for AR/VR applications. An Arm Cortex M0 processor is integrated in the sensor, which, when utilized in conjunction with the firmware from CEVA Hillcrest Laboratories, provides a sensor fusion of the accelerometer, gyroscope and magnetometer. The BNO085 is connected to the Adafruit QtPy RP2040 microcontroller via an I2C connection. The QtPy RP2040 is connected over a USB UART serial connection to the workstation, thereby providing the sensor data for subsequent processing. Consequently, the microcontroller is responsible for the initialization of the IMU, the access of the data and the transmission to the tracking system. As previously referenced, the DisplayPort cable and power connections, in conjunction with the USB cable for the IMU breakout board, are routed through a watertight tube that extends from the water to the computer and the external setup.

3.4 The Software Environment

ROS 2 Iron is chosen as the software framework foundation of the project to process the various sensor and camera inputs and to determine the head pose. Different ROS nodes are utilized for the sensor data acquisition, the sensor fusion and the transmission of the pose to Unity. The Spinnaker Camera Driver for the FLIR BFS-PGE-23S3C-C cameras is embedded as a ROS node in the project. Each of the camera ROS nodes employs the AprilTag library to identify the various fiducial tags present in the raw images. The detections are evaluated and the positions of the cubic structure and the headset in relation to the camera are determined using the AprilTag library. The tracking node updates the message whenever a new position and rotation is computed and published as ROS topic.

The software for the headsets in rev1 and rev2 was designed in a syncronous fashion, i.e., it waited for all four cameras to transmit new image data and subsequently using the combined image data to calculate the position and orientation of the headset. We call this optical tracking system *OTS old*. With *OTS new* we denote the tracking, that makes the first processing step of the camera data in the image node independent of each other for which we achieve faster tracking times. It also includes the IMU built in rev3 of the headset.

The CEVA Hillcrest Laboratories firmware SH-2 optimized for AR/VR applications is running on the BNO085 inertial measurement unit. This firmware offers different data outputs that result from internal sensor fusion and calibration algorithms for AR/VR purposes.

The AR/VR Stabilized Game Rotation Vector delivers a self-correcting position estimation utilizing the onboard accelerometer and gyroscope measurements. Accumulated errors in the integration of the gyroscope measurements are corrected by estimations from roll/pitch angles delivered by the accelerometer data. Another data output utilized for this project is the Linear Acceleration. This output results from the accelerometer data which has been improved by calibration. Whenever new sensor events are available, those are received by the QtPy microcontroller and serialized for further transmission, corresponding to the data output of either rotation vectors or linear accelerations. Due to the onboard filtering of the rotation vector related data of the SH-2 firmware, the outputs received on the microcontroller result in stable values without noticeable jumps or wrong values. Therefore, the rotation vector data is forwarded directly to the PC without further processing on the microcontroller using the UART serial protocol. A low-pass filter implemented on the QtPy microcontroller serves the function of smoothing the overall data and eliminating the higher frequencies that appear as noise in the dataset.

Since the IMU data is transferred to the PC and the OTS system calculates the pose in a ROS node utilizing the AprilTag library for object tracking, the final determination of the player pose is now carried out based on the IMU and OTS data. After transforming the coordinate frames and calibrating of IMU and OTS rotation vector a Kalman filter in employed for sensor fusion, to achieve the objective of a robust head tracking with minimal delay and lag. To determine the pose of the headset, we use the IMU rotation vector output for orientation determination, and OTS and IMU Kalman filter sensor fusion for position determination. A lightweight solution for a one-way transfer of the pose from ROS to Unity is presented.

The overall workflow of the data is visualized in Fig. 7 and works similar to the Unity Robotics Hub which provides the ROS-TCP-Connector, but without serializing every available ROS topics over TCP. The TCP Server Socket is a ROS node that hosts a TCP socket for a client to connect to. Upon the publication of each new pose the TCP server node is responsible for receiving the pose and calibration information. Subsequently, the server node disseminates this information to the connected client via TCP. In this particular instance,

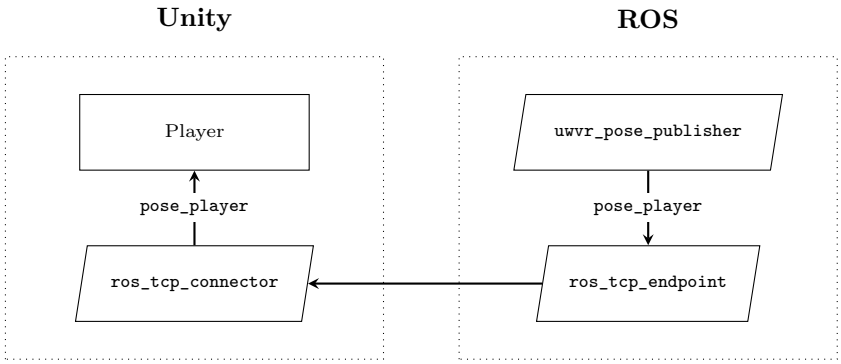

Figure 7 Visualization of the lightweight TCP communication solution between ROS and Unity[2].

the TCP client is initiated through a Unity script, which is attached to the Unity game object player. It extracts the pose information and adjusts the position and orientation of the player accordingly. The calibration information is used to determine whether the artificial horizon should be displayed.

4 Experiments and Results

Fig. 8 shows screenshots tracking system while conducting a basic EVA movement experiment. For this experiment, the user is standing upright next to the structure with the handrail. After moving into a horizontal position, the following sequence is performed: Translation left ↔ right, back ↔ front, down ↔ up and the rotating the head Roll → Yaw → Pitch. This simple movement sequence is performed to showcase the full 6-DoF tracking capabilities of the system.

4.1 Robustness Testing

The objective of the robustness evaluation tests is primarily to assess the performance and general functionality of the underwater VR headset. The evaluation process was primarily divided into two categories: (1) Delay, (2) Robustness.

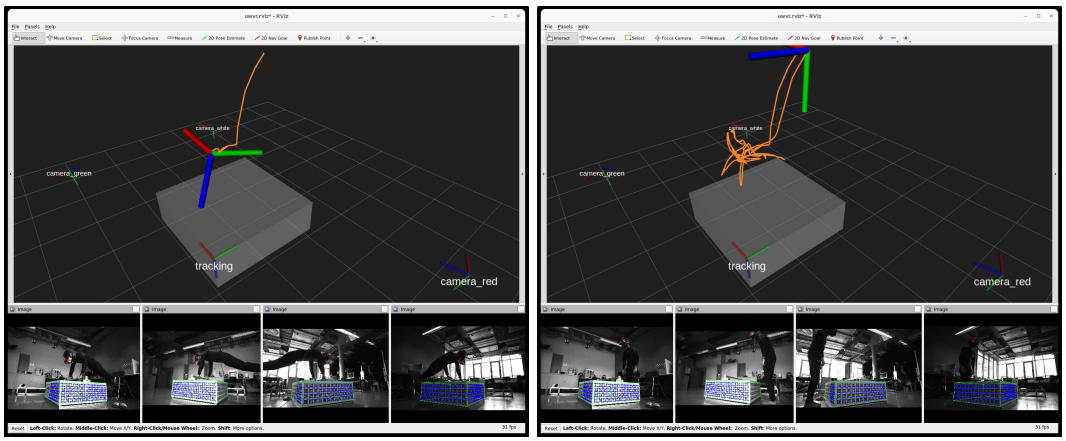

Figure 8 Visualized tracking of the conducted EVA movement experiment.

Table 1 Mean μ and standard deviation σ of the delay measurements utilizing the new TCP server node vs. the ROS-TCP-Connector for IMU and the optical tracking system (OTS).

	ROS-TCP-Connector		TCP server	
	IMU	OTS new	IMU	OTS new
Mean	13.92 ms	68.23 ms	4.34 ms	58.70 ms
Stdev	6.18 ms	9.26 ms	1.66 ms	8.96 ms

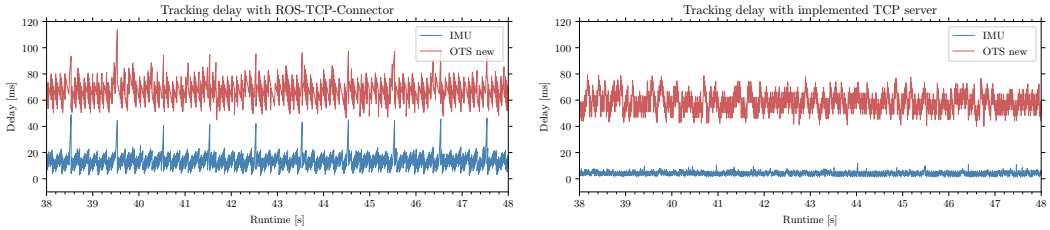

Figure 9 The overall delay of the camera tracking system in contrast to the IMU utilizing the ROS-TCP-Connector (left) and the new TCP server (right). The delay corresponds to the time from when the data is first received to when it is finally processed in Unity.

Measuring time delays through the system

The objective of this experiment is to calculate the time difference from the original recording of the sensor data to the final display of the pose in Unity. It corresponds to the delay between the user's input, in this case a head movement and the actual display in the virtual environment in the VR headset. There exist various solutions for determination of this difference. One option, which is utilized for this experiment, is to obtain a timestamp of the sensor data at the earliest possible point, ideally at the point of data collection. This timestamp is then tracked through the system in conjunction with the sensor data. Given that the optical tracking system and the inertial measurement unit provide two distinct sensor inputs to the system, these inputs result in different methodologies for computing and forwarding their respective timestamps.

At first, the delays were measured with the ROS-TCP-Connector selected as the transmission method between ROS and Unity. When utilizing the TCP server method of transmitting the timestamps to Unity, a general decline in the delay times is observable, as seen in Table 1 and Fig. 9. The mean IMU delay reduced about 9.58 ms similarly to the OTS delay of about 9.53 ms. Moreover, the implementation of the new TCP server has effectively eliminated the periodic peaks that previously led to additional lag.

Measuring data robustness

In the following, the data from the various tracking approaches is presented graphically to illustrate disparities and improvements in terms of data robustness. A movement sequence of approximately 185 seconds was recorded. This sequence includes all types of translation and rotation movements.

The initial comparison will be of the positional data. It is important to note that the Kalman filter sensor fusion uses the new OTS tracking as the basis for the inputs. To ensure consistency, the subsequent graphics are constrained to the x-axis of the headset's position.

Fig. 10 (top left) illustrates the enhancements made to the optical tracking system. While the old OTS exhibits a higher number of outliers and deviations, the new OTS's data points are more coherent and smoothed, showcasing an increased stability and contiguity of the

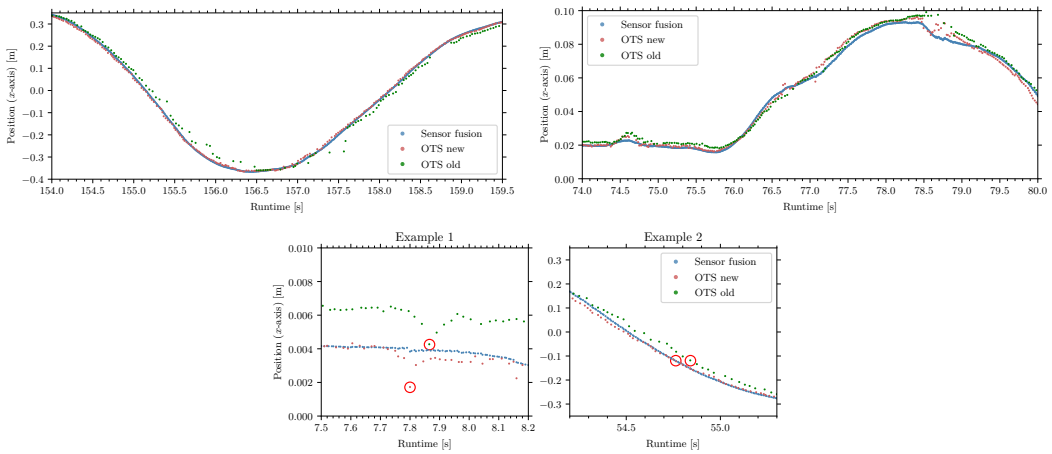

Figure 10 The headset's position in the x-axis of the various tracking systems is visualized over a 5.5-second (above left) and 6-second (above right) period. The sensor fusion with Kalman filter is compared to the old and new version of the optical tracking system. Below: Illustration of two examples of x-axis position tracking to determine the time differences between OTS new and OTS old. The data points marked with a red circle, which represent matching features in the tracking, are compared in each case.

optical tracking system. It is also noticeable that the frequency of data points from the old optical tracking version is significantly lower, particularly around the 157-second mark, as one or more cameras were no longer be able to track the tags. Consequently, substantial lags and delays are experienced at this point, which has a considerable impact on the user experience. In contrast, the sensor fusion tracking based on the Kalman filter delivers the highest and most consistent data rate, as it estimates new data points in the prediction step, if further OTS data is missing. the sensor fusion calculations are characterized by the smoothness of the trajectory, since minor inaccuracies in the optical tracking are corrected. The smoothing effect of the sensor fusion is even more evident in Fig. 10 (top right). To estimate the time differences from the positional tracking as well, Fig. 10 (bottom) displays two examples to estimate the delay between the systems. Given that the Kalman filter for sensor fusion utilizes the new version of the OTS as the system input, the computed position is significantly influenced by its data. Consequently, there is negligible time difference between the two systems. For measuring the overall time improvements for the position tracking, a more effective approach is to compare the new OTS version with the previous iteration.

A comparison of the rotation data is made between the IMU and the new and old versions of the optical tracking system. As mentioned before, the rotation vector returned by the IMU is directly used for the rotation tracking, after a transformation to the OTS coordinate frame in the calibration step. Therefore, the rotation tracking in the sensor fusion algorithm is entirely distinct from the optical tracking system.

In the subsequent graphics are constrained to the quaternions y-parameter of the headset's orientation. The y-parameter was selected because a good continuous trajectory of the data points was recognizable here. As illustrated in Fig. 11 (left), the rotation tracking y-parameter of the aforementioned tracking methods is plotted in a trajectory over a span of 10.5 seconds. The higher data rate of the IMU values is noticeable, which leads to more accurate tracking with less delay and lag between the individual data points. A deviation of the individual trajectories in both axes is also apparent. In Fig. 11 (right), the time difference between the system is evaluated from the single trajectories. The red circles denote the points that are being compared.

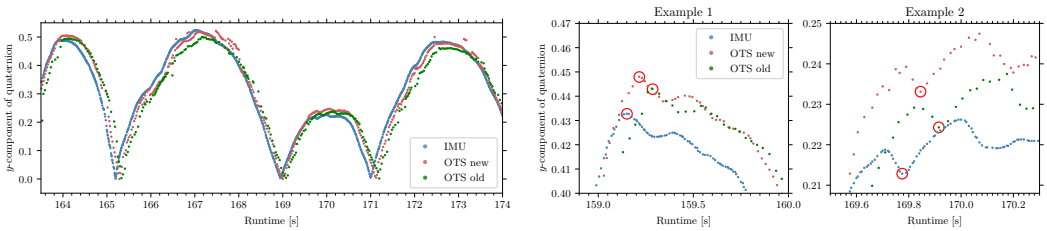

Figure 11 Left: The y-component of the headset's rotation quaternion is visualized over a 5.5-second period. The sensor fusion with Kalman filter is compared to the old and new version of the optical tracking system. Right: Two examples of the y-component of the rotation quaternion to determine the time differences between IMU, OTS new and OTS old. The data points marked with a red circle, which represent matching features in the tracking, are compared in each case.

Table 2 Summary of the overall latency/delay improvements of different tracking solutions. Time difference between tracking methods in ms.

Tracking methods	Position		Rotation	
	Example 1	Example 2	Example 1	Example 2
OTS old - OTS new	66	78	70	70
OTS new - IMU	-	-	65	70
OTS old - IMU	-	-	135	140

Table 2 summarizes the time differences measured thus far for the different tracking solutions utilized in the robustness tests of translation and rotation. It is evident that the time differences between OTS old and OTS new for the translation and rotation correspond to each other with a mean difference of 71 ms. Time differences between sensor fusion position and OTS were not recorded, as there are no significant time differences between sensor fusion and OTS new.

4.2 Field-testing at ESA's Neutral Buoyancy Facility

In a campaign at the European Astronaut Center in Cologne the underwater VR headset has been tested within the pool of the Neutral Buoyancy Facility (NBF). This visit resulted in an occasion to have the VR headset assessed by a group of test persons, including the ESA astronauts Matthias Maurer and Marco Sieber, along with VR experts in the domain of astronaut training purposes and an astronaut training instructor (referred to as test subjects in the following test evaluation).

The cameras and cubic structure are mounted on a height-adjustable platform in the NBF, enabling a system testing in the dry prior to deployment. The system is then lowered exactly to the desired water depth of 1.5 meters, at which depth the tests are conducted, as seen in Fig. 1.

To ensure a consistent experience for all test subjects, a sequence of movements and tasks was defined in advance. This sequence is discussed with the participants during a pre-test briefing and also communicated via the headset during the dive. The initial task of the test dive is to grip the handrail as a reference point and to become familiar with the virtual environment. Subsequently, the calibration between the IMU and the OTS needs to be performed.



Figure 12 Left: Astronaut Matthias Maurer preparing for setting up the underwater VR headset. Right: Test including a safety diver.

The subsequent step in this process is to take a closer look around and to become more familiar with the surroundings. One such example is the observation of the moon. The goal is to identify any differences between the tracking robustness before and after the calibration step. Given that the tracking is based purely on the optical system prior to calibration, comparisons are made with the performance improvements of the sensor fusion. Subsequently, movements such as translation in the x, y, z-direction and rotations in roll, pitch, and yaw are carried out separately in order to gain further impressions of the tracking. The next task requires moving beyond the left and right edges of the cubic platform to be able to observe the lateral surfaces. The ESA logo is randomly distributed on one of both sides for each participant. The task at hand is to locate the logo and report its position via the headset communication to the diving instructor. Subsequently, the subjects are instructed to orient their heads above the four colored markers positioned at the corners of the platform, while continuing to hold onto the handrail. The sequence of the markers is communicated via the headset by the diving instructor. Finally, each participant is given a period of time for unrestrained movement within reach of the cubic platform, thereby further experiencing the simulation of floating in the virtual environment in zero gravity. After carrying out the procedure, the participants are interviewed and asked to share their impressions and experiences during the test of the underwater VR headset.

Calibration and tracking

All test subjects agreed that the calibration process for the tracking was uncomplicated and quickly completed due to the explanation in the briefing beforehand. The primary differences after the successful calibration that were observed included a significantly higher frame rate and fewer jumps in the pose determination. However, the participants still occasionally noticed smaller jumps in the pose after the calibration. It was once mentioned that these were noticeable when objects were viewed in proximity. As soon as objects were viewed from a distance, no jumps have been observed. One of the test subjects also mentioned experiencing jumps in the world when having the arms close to the head, which led to an occlusion of the AprilTags on the headset. Overall, all participants agreed that the tracking got improved after the calibration step.

Perception of delay

The delay is a critical factor in the overall tracking of a VR headset. As one of the main points of this work was to improve the head tracking, the test subjects were explicitly asked about their impressions of the tracking delay.

The participants' perceptions of the delay varied. Three out of the five individuals did not observe any disturbing delays, particularly with the slower movements of the head due to the inertia of the water. Two test subjects reported a noticeable delay when focusing on objects in the near environment, such as the cubic structure or handrail. One participant noted that this delay was particularly present during translational head movements. However, both subjects agreed that there was minimal to no perceptible delay when focusing on objects in the far environment.

One person of the group had already tested the old version of OTS tracking before as part of the collaboration between ESA and the University of Würzburg and therefore could compare it to the current version. It was mentioned, that the delay has improved significantly compared to the old version, which had a perceived delay of hundreds of milliseconds

Navigation and tasks

The general feedback regarding the orientation and navigation within the virtual environment was that there were no problems overall. Therefore, it was not difficult to perform rotation and translation movements. However, the majority of the test subjects agreed that a change in the design of the handrail would significantly improve the overall navigation underwater. Some of the ideas included the addition of a second handrail to increase the mobility for simple movements, as well as adding vertical end pieces to the handrails.

The tasks performed underwater have been reported as relatively straightforward and not challenging, and are more comparable to system checks than to actual tasks. From the per- spective of astronaut training, it has been noted that the tasks were not comparable to those performed during astronaut training. This is due to the fact that operating different types of tools plays a significant role in Extra Vehicular Activity (EVA) procedures. It was also noted that communication through the headset played an important role during the tasks, as otherwise visual contact with the outside was not given.

Motion sickness

Motion sickness must be not an issue for the headset to be used for training, which extends over longer periods of time. For this reason, the test persons were explicitly asked how they felt when wearing the headset.

During the tests, none of the test subjects experienced signs of motion sickness. Two of the subjects had no signs of any discomfort. Otherwise, it was reported that it felt unfamiliar at first not being able to see the own hands. It was also mentioned on one occasion that the previously stated problems with focusing on close objects felt slightly uncomfortable, which could possibly become a problem for longer testing periods. Finally, it was noted that the higher weight of the mask did result in a slight discomfort.

Immersion

Since the headset is mounted onto the diving mask, there is a greater distance between the lenses and the display, resulting in a smaller field of view. Therefore, this section will summarize how this affected the immersion of the virtual environment and how the simulation of zero gravity was experienced.

Overall, all participants reported a full immersion into the virtual environment. The visible edge area of the diving mask was mentioned briefly, but it was ignored after some time as the test subjects became more attracted to the virtual world. It was also noted that it was challenging to find the right focus initially. The buoyancy of the mask caused a slight

shift, resulting in a change in focus compared to the first wearing of the headset outside the water. Once the correct focus underwater was determined, the field of view was described as being both adequate and not limiting.

With regard to the simulation of a zero gravity environment, it was noted that both the inertia of the headset in the water and the overall water resistance were experienced. Otherwise, the floating experience was reported to be good and realistic, provided that the diving suit and jacket were correctly buoyant.

Given Matthias Maurer's prior experience with zero gravity during his stay on the International Space Station, it was particularly fascinating to ask for a comparison between true weightlessness and of the underwater VR simulation. Regarding his experience, the effect of underwater VR is quite similar. However, he reported that in actual weightlessness, one is never stable and constantly floating around. In contrast, in the underwater VR simulation, it was easy to maintain a stable floating position with hand movements due to the water environment.

5 Conclusions and Outlook

It was shown that the sensation of weightlessness in space can be achieved by combining a VR headset within an underwater neutral buoyancy environment. The combination of inertial and optical sensors has been demonstrated as a viable approach for six-degree-of-freedom tracking underwater. A latency of 146 milliseconds was identified as the pure technical delay of the initial version of the study. However, substantial irregularities in the data rates resulted in an actual perceived delay of 268 ms on average. The Kalman filter sensor fusion effectively eliminated these irregularities and significantly increased the data rate. The integration of an additional inertial sensor led to a substantial reduction in the delay, with a resulting latency of approximately 7 ms for rotations and approximately 76 ms for translations.

Needless to say, a lot of work remains to be done. We plan to make the shift from outside-in tracking to inside-out tracking, to be able to capture hand poses. Furthermore, we plan to add tracking of equipment and tools.

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Gaze Beyond Limits: Integrating Eye-Tracking and Augmented Reality for Next-Generation Spacesuit Interaction

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Abstract

Extravehicular activities (EVAs) are increasingly frequent in human spaceflight, particularly in spacecraft maintenance, scientific research, and planetary exploration. Spacesuits are essential for sustaining astronauts in the harsh environment of space, making their design a key factor in the success of EVA missions. The development of spacesuit technology has traditionally been driven by highly engineered solutions focused on life support, mission adaptability and operational efficiency. Modern spacesuits prioritize maintaining optimal internal temperature, humidity and pressure, as well as withstanding extreme temperature fluctuations and providing robust protection against micrometeoroid impacts and space debris. However, their bulkiness and rigidity impose significant physical strain on astronauts, reducing mobility and dexterity, particularly in tasks requiring fine motor control. The restricted field of view further complicates situational awareness, increasing the cognitive load during high-precision operations. While traditional spacesuits support basic EVA tasks, future space exploration shifting toward long-duration lunar and Martian surface missions demand more adaptive, intelligent, and astronaut-centric designs to overcome current constraints. To explore a next-generation spacesuit, this paper proposed an in-process eye-tracking embedded Augmented Reality (AR) Spacesuit System to enhance astronaut-environment interactions. By leveraging Segment-Anything Models (SAM) and Vision-Language Models (VLMs), we demonstrate a four-step approach to enable top-down gaze detection to minimize erroneous fixation data, gaze-based segmentation of objects of interest, real-time contextual assistance via AR overlays and hands-free operation within the spacesuit. This approach enhances real-time situational awareness and improves EVA task efficiency. We conclude with an exploration of the AR Helmet System's potential in revolutionizing human-space interaction paradigms for future long-duration deep-space missions and discuss the further optimization of eye-tracking interactions using VLMs to predict astronaut intent and highlight relevant objects preemptively.

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Keywords and phrases Augmented Reality (AR), Eye-Tracking, Cognitive Load/Workload, Segment Anything Model (SAM), Visual Language Models (VLMs)

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1 Introduction

The Apollo program marked a pivotal era in human space exploration, demonstrating the feasibility of extravehicular activities (EVAs) on other planets [14]. As space agencies and private enterprises shift their focus toward long-duration and deep space missions, EVAs are expected to become more frequent and complex [3]. Tasks including troubleshooting unexpected equipment failures and adjusting habitat assembly based on terrain constraints, require astronauts to make real-time decisions based on dynamic environmental conditions, making human involvement essential. In these missions, spacesuits serve as indispensable tools that provide life support, protect astronauts from extreme environments, and enable operational tasks in microgravity or on planetary surfaces [8].

Early spacesuits, such as the Apollo A7L, were tailored for short-duration EVAs, focusing on pressure integrity while carefully balancing the inherent trade-off with mobility for lunar exploration [20]. The introduction of the Extravehicular Mobility Unit (EMU) brought improvements in flexibility and life support capabilities, supporting gradually increasing EVA durations during the Apollo program [31] and enabling more complex extravehicular tasks in microgravity [27]. More recent advancements have begun integrating augmented reality (AR) technology into spacesuit systems to enhance astronaut interaction with their surroundings [2].

However, modern spacesuit designs still impose significant challenges on astronauts during EVAs. The bulkiness and rigidity of current spacesuits severely restrict fine motor control, such as adjusting delicate instruments or assembling small components, making precise manipulations exceptionally difficult and leading to increased task duration and fatigue [23]. This forced exertion can further lead to musculoskeletal injuries and significant physical workload, compromising astronaut health and operational performance [5]. Additionally, the spacesuit helmets significantly restrict astronauts' field of view, creating blind spots and limiting peripheral vision. This limitation is primarily caused by the rigid helmet structure being fixed to the torso, which prevents head-turn-based gaze shifts and requires full upper-body movement to adjust the line of sight, thereby compromising situational awareness, operational efficiency, and safety [11]. Despite recent advances in speech recognition technology, the communication constraints posed by spacesuits - including occluded microphones and ambient noise from life support systems - can significantly reduce the reliability of conventional voice commands for AR interface interaction, particularly in dynamic EVA scenarios [16]. Certain control operations still rely on command signals sent from mission control on Earth, limiting astronauts' ability to independently execute critical adjustments in real time [17].

The next generation of spacesuits has to evolve into intelligent and interactive systems, enhancing both astronaut efficiency and well-being to enable more advanced missions with higher efficiency [1]. Real-time interaction and control will be a key focus, with AR displays providing contextual information and hands-free operation for seamless engagement with the environment. Beyond operational improvements, future spacesuits will integrate physiological and cognitive monitoring to assess astronaut workload, fatigue, and stress levels, enabling adaptive support for astronaut health in long-duration missions [30]. This will significantly extend the operational capabilities and efficiency of crewed surface and micro-g operations at a higher comfort level for the astronauts.

This paper posits that eye-tracking technology can be integrated with AR interfaces in spacesuit helmets to enhance astronaut-AR interaction efficiency. Unlike prior AR-integration attempts that treat astronauts as passive recipients of visual overlays, our system enables active, gaze-based interaction with the environment. By combining Segment-Anything Models

(SAM) [34] with gaze detection, the system segments only the objects astronauts are focusing on, reducing AR clutter and ensuring task-relevant information display, while Vision-Language Models (VLMs) [21] analyze segmented objects to provide real-time contextual understanding. Eye-tracking features, such as blink detection, can serve as hands-free control commands, allowing astronauts to navigate interfaces and execute tasks effortlessly, while pupil dilation functions as a cognitive assessment metric, enabling real-time monitoring of astronauts' psychophysiological state during EVAs. In doing so, we argue that this approach transforms spacesuits into adaptive, intelligent systems that enhance both operational performance and astronaut well-being in long-duration deep-space missions.

In the remainder of the paper, we first review the contemporary technology for spacesuits and the limitations of current spacesuit interaction. We then present our enhanced eye-tracking-integrated AR spacesuit system. We conclude by discussing the practical challenges that may arise during system deployment and a VLMs-based optimization strategy to further enhance spacesuit interaction.

2 Spacesuit Development

2.1 Contemporary Technology for Spacesuit

Over the past six decades, spacesuits have evolved from basic high-altitude pressure garments into sophisticated miniature spacecraft, incorporating essential life support, environmental protection, mobility, communication, and emergency survival functionalities [8]. Life support systems have transitioned from basic oxygen setups, with current research focusing on achieving greater respiratory efficiency and more effective thermal regulation. Protective capabilities have improved through material optimization, enabling resistance to extreme temperature fluctuations, radiation exposure, and micrometeoroid impacts. Advances in joint design have enhanced mobility, allowing astronauts greater flexibility in executing tasks, though this improved flexibility remains far from sufficient. Communication systems have transitioned from conventional radio transmission to integrated helmet microphones, significantly improving clarity and usability. Furthermore, modern spacesuits incorporate automated pressurization mechanisms to enhance emergency survival rates.

To further enhance astronaut performance and situational awareness during EVAs, recent advancements are integrating AR/XR and human-computer interaction technologies into spacesuit design. NASA is developing the Joint AR system – an augmented reality technology tested in virtual reality – to enhance lunar surface navigation and mission execution while addressing challenges such as information overload, attention demands, and environmental perception [18]. ESA explores the integration of XR technology with parabolic flight-based astronaut training for lunar missions and proposes practical guidelines for applying XR tools in future long-duration lunar operations [28]. Among these, Helmet-Mounted Displays (HMDs) provide astronauts with real-time mission data [29], while eye-tracking technology enables intuitive interaction with onboard systems and external environments [9]. The following sections explore these two key innovations and their implications for next-generation spacesuit development.

Helmet-Mounted Display (HMD)

A Head-mounted Display (HMD) is a device that directly projects information into the user's field of view [29]. HMDs were initially developed for military and aviation applications, primarily serving as targeting systems in fighter jets and helmet-mounted sighting systems

to enhance operational efficiency and pilots' situational awareness. With technological advancements, HMDs have expanded into various fields, including healthcare, industrial applications, and consumer electronics [22].

In space exploration, as human missions become more complex, HMDs are emerging as a critical component in modern spacesuit design to facilitate real-time information display. Particularly for the upcoming Artemis lunar mission, NASA has designated solutions such as wrist-mounted displays and HMDs as key requirements for the development of the next-generation extravehicular mobility unit (xEMU) [1]. Due to the unique challenges of lunar environments – such as the difficulty of depth perception caused by uniform terrain and unidirectional sunlight – astronauts often struggle to accurately estimate distances or navigate effectively. The integration of HMDs aims to provide astronauts with vital information, including biometric monitoring, navigation assistance, and mission-related data, thereby enhancing autonomy and reducing reliance on ground control [1].

Building upon traditional HMD technology, AR Head-Mounted Displays (AR-HMDs) integrate virtual content with real-world environments by using optical combiners and advanced display systems. Unlike conventional HMDs, which primarily focus on overlaying digital data, AR-HMDs enable real-time interaction with the environment, making them particularly suitable for complex operational settings such as space exploration. Optical waveguides and freeform prism optics allow for a lightweight and transparent display, ensuring critical mission data can be seamlessly integrated into the astronaut's field of view without obstructing vision [10]. Additionally, AR technology provides a more intuitive and immersive interface compared to wrist-mounted displays [26], addressing key challenges such as limited dexterity and complex information retrieval during EVAs. Recognizing these benefits, the NASA/Johnson Space Center has conducted multiple feasibility development programs exploring the integration of HMDs into Extravehicular Mobility Units (EMUs) [25]. These studies have resulted in prototype binocular and biocular HMD systems utilizing conventional optical elements (e.g., glass lenses and beamsplitters) and holographic optics. Furthermore, research efforts have explored the potential for integrating voice recognition capabilities, allowing astronauts hands-free access to mission-critical information through their HMDs.

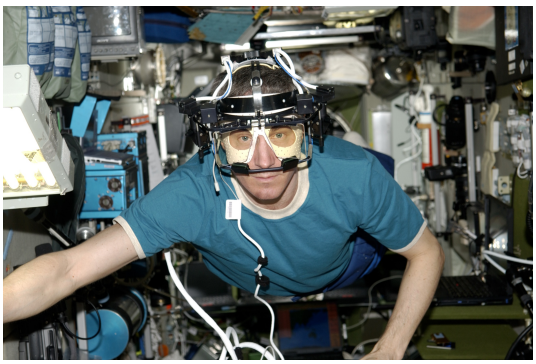


Figure 1 Cosmonaut Sergei Krikalev wearing ESA's Eye Tracking Device during Expedition 11 to the International Space Station in 2005 [12]. (Credit: ESA/NASA. © ESA Standard Licence).

Eye Tracking Device (ETD)

Eye-tracking technology has evolved as a fundamental tool in applied cognitive science and human-computer interaction (HCI), enabling real-time monitoring of visual attention, cognitive load, and user intent [4]. By capturing gaze direction and pupil dilation, eye-tracking

systems facilitate hands-free interaction and real-time data capture, providing insights into cognitive processes. These capabilities have been widely adopted in various fields, including performance psychology and human factors research, to measure task performance, visual attention, cognitive load, and affective states.

The European Space Agency (ESA) conducted experiments aboard the International Space Station (ISS) to investigate how microgravity affects astronauts' eye movements and balance (Figure 1) [13]. Researchers developed a helmet equipped with high-performance image-processing chips to track eye movements without interfering with the astronauts' tasks. The findings revealed that weightlessness impacts balance and eye movement control, indicating that our sensory-motor systems rely on gravity for orientation. These insights are crucial for designing eye-tracking systems that function effectively in space environments.

2.2 Challenges in Spacesuit Design

Modern spacesuit designs have prioritized life support, durability, and mobility, yet fundamental limitations persist. The current generation of spacesuits presents significant ergonomic and operational challenges, particularly as space exploration expands to longer missions on the Moon and Mars. These challenges can be categorized into three key areas: mobility and dexterity restrictions, limited interaction constraints, and lack of situational awareness.

Mobility and Dexterity Restrictions

Spacesuit bulkiness and rigidity impose severe restrictions on astronauts' mobility and dexterity [23]. During every movement of a spacesuit joint within the pressurized environment of the spacesuit, the volume within the suit is compressed or extended, which creates significant resistance against movement, making even simple tasks physically demanding. One of the most critical limitations is the lack of fine motor control, especially in gloves, which affects astronauts' ability to perform delicate operations such as instrument adjustments, sample collection, and tool handling.

In microgravity, astronauts face additional difficulties due to the lack of stable ground support, which increases the physical strain of maneuvering while counteracting inertia. On planetary surfaces such as the Moon and Mars, the added complexity of navigating uneven terrain while wearing a stiff suit – and managing the inertia of the suit's mass – further increases the risk of falls and inefficient locomotion.

Limited Interaction Constraints

Voice commands are crucial for hands-free control during EVAs, allowing astronauts to operate systems without manual input. However, they are highly susceptible to interference from ambient noise generated by life support systems, radio disruptions, and microphone inconsistencies [16]. These factors can cause misinterpretations, delays, or failed commands, reducing operational efficiency and increasing workload.

Moreover, spacesuit gloves, designed for protection and pressurization, significantly restrict finger dexterity [23]. This makes precise interactions with buttons, switches, and touchscreens difficult or even impossible, further complicating equipment operation.

Situation Awareness

The helmet design of current spacesuits significantly limits astronauts' peripheral vision and provides minimal real-time digital information display. As a result, astronauts often rely on written procedures or pre-memorized sequences learned through repetitive training, which

increases the risk of spatial disorientation and reduces situational awareness during complex EVAs. Additionally, astronauts retrieve real-time environmental data based on mission control or pre-memorized details, which is inefficient, especially in deep-space missions with long communication delays [11].

Furthermore, current spacesuits incorporate very few embedded sensors, and many bioinstrumentation signals, such as electrocardiogram readings and body temperature data, are transmitted exclusively to ground-based medical teams, restricting astronauts' ability to monitor their own vitals in real-time [17].

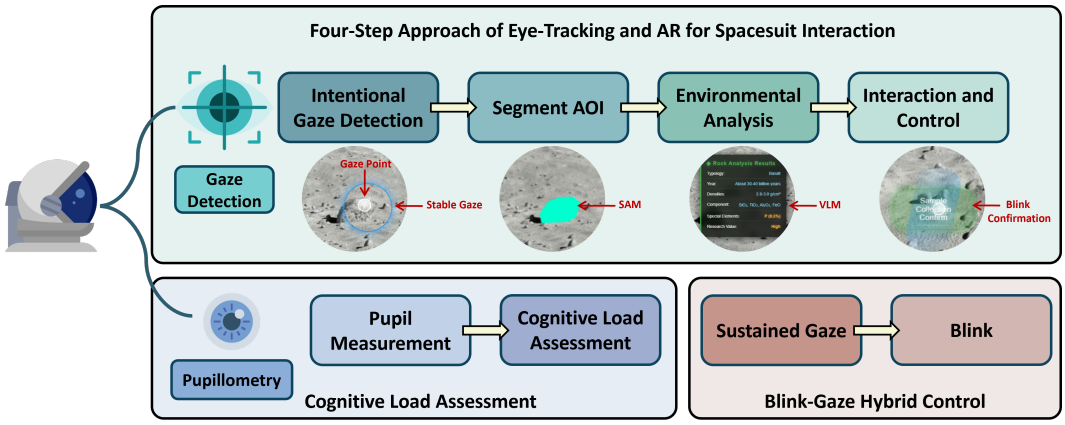


Figure 2 Framework of the Proposed four-step approach for Eye-tracking and AR Interaction in Spacesuits.

3 Eye-Tracking and AR for Next-Generation Spacesuit

3.1 Four Step Approach

To meet the increasing need for more interactive spacesuits in future long-duration and deep-space exploration missions, we propose an AR helmet system that integrates eye-tracking technology. By leveraging the Segment Anything Model (SAM) [34] and Vision-Language Models (VLMs) [21] to enhance astronauts' efficiency and safety during EVAs. The study is in the process of developing a four-step approach to enhance the next-generation spacesuit (Figure 2). First, it employs eye-tracking technology to capture astronauts' real-time gaze point and will develop an algorithm to distinguish top-down gaze from bottom-up responses. Second, it utilizes gaze data as an input prompt for the SAM to automatically segment Area of Interests (AOI). Third, the VLM provides a real-time environmental understanding of segmented AOIs, delivering intuitive information overlays through AR. Finally, based on blink detection, the system enables hands-free interaction and control. The following sections will elaborate on the implementation of these four key steps.

Step 1: Gaze Detection

Traditional gaze-based interaction systems often suffer from the Midas Touch problem [33], where bottom-up fixations and false detections due to involuntary eye movements may trigger unwanted commands, necessitating a more robust mechanism to distinguish top-down gazes from stimulus-driven ones. To address this challenge, our system will employ a two-stage approach to reduce the impact of the Midas Touch phenomenon on the gaze-based system.

Eye-movement modality recognition (EG-NET) and zonotope set-membership filtering (ZSMF) are two algorithms to enhance gaze detection accuracy [36]. EG-NET differentiates between fixations, saccades, and outliers by integrating eye image features and gaze dynamics, filtering out involuntary blinks and tracking losses. To further refine accuracy, ZSMF eliminates noise and stabilizes gaze signals in real time, leveraging an unknown but bounded (UBB) noise assumption for robust performance in dynamic space environments. Together, these methods ensure that only deliberate gaze fixations are processed, providing a reliable foundation for gaze-based segmentation and interaction.

Pupil size is widely recognized as a physiological indicator of cognitive load and attentional engagement [32], which refers to the burden on the brain in processing information, decision-making, and problem-solving. [32] proposed a methodology for integrating an online modeling algorithm that fits task-evoked pupillary response (TEPR) curves to identify temporal variations in cognitive workload. The study indicated that TEPR, which is often used to distinguish between conscious and unconscious blinking, is more strongly driven by luminance changes than by cognitive load, thus a smart filtering mechanism is needed to eliminate light-induced noise and ensure only intentional interactions are captured. By continuously monitoring variations in cognitive load, it can dynamically differentiate between top-down and bottom-up gaze behaviors. As a result, this adaptive filtering mechanism reduces the frequency repositioning of the gaze point, thereby minimizing unnecessary updates and preventing visual clutter.

Furthermore, to reassure that the point of top-down gaze is accurate, the system will first show the steady gaze point after a two-second threshold, followed by a voluntary blink to confirm the steady gazing area. Research [7] has demonstrated that a longer trigger duration can improve this problem, but durations tend to be inconsistent across studies due to different individuals. Blinking is a natural interaction and does not cause Midas Touch problems. Although prior study [24] demonstrated that the double-blink trigger yields the best performance, is had also highlighted that blink frequency tends to increase under physical fatigue or high cognitive load, which may result in unintentional activations. Building upon these insights, our system will build a blink-gaze hybrid control system that ensures accurate and intentional interactions while mitigating issues related to uncertain trigger duration and fatigue-induced blink variability.

Step 2: Segmenting the Area of Interest (AOI)

Once the astronaut's gaze is accurately detected and stabilized, the system will utilize the Segment Anything Model (SAM) [34] to automatically segment the Area of Interest (AOI) based on real-time eye-tracking data. By transforming gaze fixation points into input prompts, SAM generates highly precise pixel-level segmentation masks, effectively isolating relevant objects within the astronaut's field of view, such as Martian terrain, control panels, scientific instruments, or potential hazards.

SAM operates on a prompt-based segmentation mechanism, where the user's gaze coordinates serve as input prompts to guide the segmentation process. The model consists of a Vision Transformer (ViT)-based backbone, which first encodes the input image into deep feature representations. When a gaze-based prompt is received, SAM processes it through a prompt encoder, mapping the fixation point onto the pre-computed image embedding. The model then generates a segmentation mask that outlines the AOI with high accuracy. This approach enables dynamic object segmentation without requiring predefined labels, making it highly adaptable for unstructured extraterrestrial environments [34].

Unlike traditional segmentation methods that rely on manual selection or predefined object categories [35], SAM allows the real-time identification of previously unseen or unstructured objects in extraterrestrial environments. This capability is particularly valuable for autonomous navigation, geological analysis, and operational decision-making, where rapid object recognition and interaction are crucial.

Step 3: Real-Time Environmental Analysis

Following the segmentation of AOIs, the system will employ Visual Language Models (VLMs) to provide real-time semantic understanding of the astronaut's surroundings [21]. This step enhances situational awareness by interpreting segmented objects, generating descriptive annotations, and delivering contextual information overlays directly to the astronaut's AR helmet display.

At the core of this process, the VLM leverages a multi-modal transformer architecture, which fuses visual embeddings with pre-trained language representations to generate meaningful descriptions of the segmented AOIs. The workflow begins with image encoding, where helmet-mounted cameras capture real-time visual input. A Vision Transformer (ViT) extracts high-dimensional features, which are then processed through a multi-modal fusion network to align the visual and textual representations. To improve accuracy and relevance, the system incorporates context-aware prompting, adjusting output information based on the astronaut's gaze behavior, mission objectives, and environmental conditions. This ensures that VLM-generated insights are task-specific and contextually appropriate, reducing cognitive overload in high-stakes EVA scenarios.

Insights from AR-based contextual learning research [21] highlight the advantages of real-time, adaptive information delivery, demonstrating that dynamic, gaze-based content adjustments significantly enhance task comprehension and user engagement. Experimental findings in AR-assisted language learning show that multi-modal interactions, where visual cues are seamlessly integrated with textual feedback, lead to deeper contextual understanding and improved retention of information. By incorporating similar principles, our system will optimize knowledge acquisition and decision-making efficiency for astronauts by ensuring timely, context-relevant semantic explanations.

Step 4: Interaction and Control

The system automatically provides options that can be acted upon based on the results of the VLM analysis. It will allow astronauts to navigate the operation menu with eye movement. Building on the previously described blink-gaze hybrid control mechanism in 3.1 (Step 1: Gaze Detection), this step applies the same principle to select action options, ensuring consistent and intuitive user input across different interface elements.

To further optimize usability, we focus on the spatial arrangement and sizing of interactive objects (IOs), preventing accidental activations while maintaining an efficient and ergonomic design. Research [24] has shown that IOs with a 55.5 mm diameter and 33.3 mm spacing significantly enhance selection accuracy and response time by reducing fixation instability and minimizing unintended selections. In our system, these parameters will guide the layout of AR-based control panels and mission-critical interfaces, ensuring that astronauts can effortlessly target the correct option without excessive cognitive strain.

Additionally, visual feedback mechanisms, such as subtle highlights or translucency adjustments, help astronauts differentiate between active selections and background elements, reducing cognitive overload in complex operational scenarios.

Beyond simple menu navigation, the system will enable astronauts to interact with mission-critical interfaces and robotic systems in real-time. For example, when operating a control panel, a sustained gaze highlights a button, and a voluntary blink confirms selection, eliminating the need for manual input. Similarly, in robotic arm operation, astronauts can lock onto an object using gaze fixation, and a blink command triggers grasping or manipulation, facilitating efficient sample collection or tool handling.

3.2 Workload Assessment

Workload refers to the overall burden an individual experiences while performing a task, including the consumption of physiological, psychological, and cognitive resources, as well as the associated stress. Analyzing workload is crucial for astronauts as it directly impacts their cognitive and physical performance during missions. Given the extreme environments and high-stakes nature of space operations, effective workload management is essential to ensuring mission success and astronaut well-being.

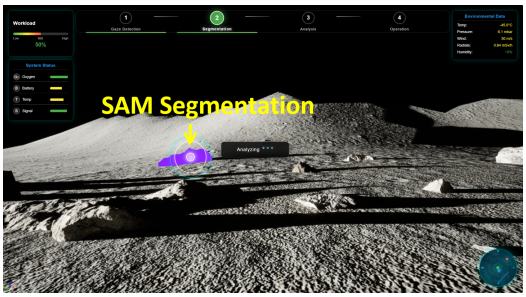
Pupil dilation has emerged as a reliable metric for assessing workload in real-time. Research has shown that increased mental effort leads to greater pupil dilation, making it a valuable indicator for workload monitoring [19]. Similarly, as measuring the cognitive load, a key approach to analyzing workload in space is through continuous tracking of pupil dilation [32]. These studies have validated algorithms that estimate cognitive demands based on pupil size without requiring prior knowledge of task onset. In space missions, with embedded eye-tracking and pupil dilation measurement technology, astronauts can now view their cognitive workload in real-time directly through the AR interface in their helmet, eliminating the need for remote monitoring and supervision fromthe ground control center. This self-monitoring capability allows astronauts to dynamically adjust their work pace during operations, thereby preventing overload-related errors and inefficiencies.

Furthermore, unlike traditional methods such as electromyography (EMG) and electroencephalography (EEG), which require sensor placement on the skin or scalp, eye-tracking-based workload assessment offers a more practical and non-intrusive solution for use in spacesuits. EMG and EEG sensors often demand direct skin contact, careful positioning, and motion artifact filtering, making them less suitable for astronauts operating in a pressurized helmet. Additionally, EEG signals are highly susceptible to electromagnetic interference, which can be challenging in space environments with fluctuating radio frequencies and onboard electronic systems. In contrast, pupil dilation monitoring via eye-tracking is fully integrated within the helmet visor, requiring no additional physical contact. Modern infrared-based eye trackers embedded into the helmet provide continuous, real-time data on cognitive load fluctuations without disrupting astronaut mobility. Furthermore, this method eliminates the need for adhesive electrodes, conductive gels, or recalibration, offering higher long-term usability and reduced maintenance requirements.

By integrating cognitive load assessment into all four operational steps (Gaze Detection, Segmentation, Analysis, and Interaction), the system dynamically adjusts UI elements to reduce astronaut fatigue and optimize task execution. For example, if the system detects a high cognitive load, it may simplify visual overlays, reduce displayed information density, or adjust interaction thresholds to prevent cognitive overload. Conversely, when load levels are low, the system can increase information granularity to enhance operational efficiency. This adaptive cognitive-aware interface ensures astronauts remain focused, efficient, and safe while performing critical EVA tasks.



(a) Step 1- Top-Down Gaze Detection: The white dot represents the astronaut's current gaze point, while the surrounding blue circle appears after a two-second fixation, indicating the system's recognition of a stable gaze.



(b) Step 2 - Segmentation of AOI: The purple-highlighted region represents the segmented AOI. The segmentation process, which is powered by the SAM, will be triggered by a voluntary blink, ensuring intentional selection.



(c) Step 3 - Real-Time Environmental Recognition: Detailed contextual information about the segmented object, which is analyzed by the VLM, is displayed as an AR overlay to assist astronaut decision-making.



(d) Step 4 - Interaction and Control: The system automatically displays available actions based on the analyzed object. A certain action will be selected by fixating on an interactive option and confirmed using a voluntary blink.

Figure 3 AR User Interface for Gaze-Based Interaction.

3.3 AR User Interface

The AR User Interface (UI) (Figure 3) in our system will be designed to seamlessly integrate gaze-based interaction, segmentation, real-time analysis, and intuitive control mechanisms, ensuring astronauts can efficiently interact with their surroundings during extravehicular activities (EVAs). The interface visually guides users through the four-step interaction process – Gaze Detection (Figure 3a), Segmentation (Figure 3b), Analysis (Figure 3c), and Operation (Figure 3d) – displayed in a progress bar at the top, ensuring clear task flow and real-time feedback.

A key feature of the AR UI is its ability to overlay contextual information directly onto the astronaut's helmet display, enhancing situational awareness without requiring physical interaction. The environmental analysis system, powered by the VLM, dynamically annotates objects in the astronaut's field of view based on top-down gaze detection and AOI segmentation. In the example shown, a rock analysis overlay provides geological data, including typology, estimated age, density, and elemental composition. This information is processed from segmented AOIs, identified via SAM based on the astronaut's gaze. Additional interactive controls allow for direct actions such as sample collection or capturing photographs via blink-based commands, as defined in the interaction and control step. Actions will also be selected through eye-tracking operations, enabling seamless and intuitive interaction without requiring manual input.

A Workload Meter continuously tracks the astronaut's workload, leveraging pupil dilation analysis from the Gaze Detection step to ensure optimal task management. The System Status Panel also provides live updates on critical parameters such as oxygen levels, battery life, temperature, and signal strength, ensuring astronauts remain aware of their life-support conditions.

To further assist in navigation, a radar system at the bottom right provides real-time positional awareness, helping astronauts track points of interest and locate mission targets efficiently. The AR UI ensures that all information is context-sensitive, hands-free, and dynamically updated, reducing cognitive load while maximizing task efficiency and safety in space operations.

3.4 Experimental Methodology

Simulated Experimental Environment

To evaluate the effectiveness of our proposed eye-tracking and AR-embedded spacesuit system, we are in the process of designing a highly realistic virtual experimental environment using Unreal Engine 5, allowing participants to experience simulated EVA scenarios. It will replicate planetary exploration tasks, including terrain analysis, robotic arm control, and control panel interactions, ensuring a comprehensive assessment of gaze-based interactions. The four-step interaction process will be fully implemented, allowing the system's cognitive load assessment and adaptive UI adjustments to be tested under realistic workload conditions. Furthermore, to analyze the constraints imposed by the bulkiness and rigidity of modern spacesuit designs, we have developed a Hard Upper Torso (HUT) simulation platform (Figure 4). The HUT system is a full-scale, modular EVA suit mockup designed to replicate lunar surface operations' ergonomics when operating in a HUT and includes a constrained field of view from the visor and sun shield. It can further integrate a shoulder cage, soft goods for limb assemblies, and onboard telemetry instrumentation.

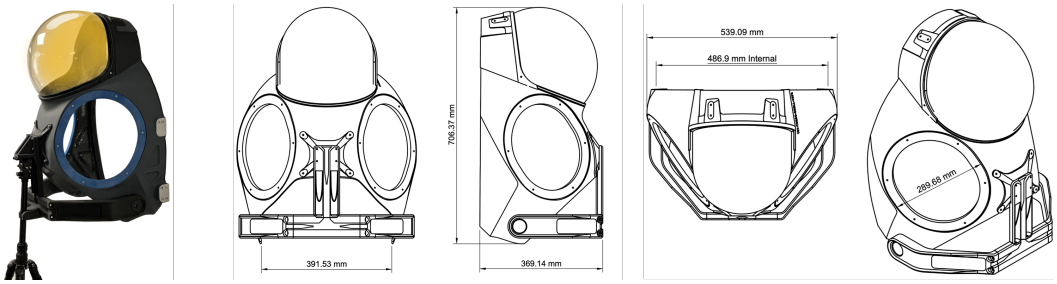


Figure 4 The Hard Upper Torso (HUT) simulation platform and its dimensions.

Participants will wear VR headsets equipped with integrated eye-tracking, interacting with virtual interfaces that closely resemble the AR overlays and control mechanisms that astronauts would use within their helmets during real operations. They will complete specific EVA tasks within the VR environment using the HUT simulation platform under varying suit configurations and operational constraints, which can validate the utility of gaze metrics as input for suit design optimization and crew training procedures.

Performance Evaluation of Eye-Tracking-Based Interaction

The study will compare the efficiency and cognitive workload of our eye-tracking-based interaction system against traditional hand-based control methods in specific operational scenarios, such as control panel manipulation and exploration of unknown terrains. The following performance metrics will be assessed:

- **Task Performance Quality:** Measured through accuracy in button selection, correct identification of segmented objects (e.g., rocks, equipment), and precision in robotic arm operations.
- **Task Completion Time**: Comparing the speed of gaze-based selection and confirmation via blink gestures against traditional manual input.
- **Cognitive Workload Assessment**: Utilizing pupil dilation variations, physiological signals, and subjective workload surveys (e.g., NASA-TLX scale [15]) to analyze psychological stress and mental effort.

4 Conclusion

As space exploration advances toward long-duration and deep-space missions, astronauts will increasingly operate in extreme environments for extended periods, facing unprecedented challenges that demand higher levels of autonomy, adaptability, and efficiency. Future missions – such as lunar base construction, Mars exploration, and deep-space probes – will require astronauts to function independently, often without real-time communication with Earth. This shift fundamentally transforms the requirements for spacesuit design and interaction systems.

Yet, the bulkiness and rigidity of these traditional spacesuits make fine motor control difficult, obstruct the astronaut's field of view, and complicate interaction with equipment and environments.

AR is recognized as an excellent interaction modality for enhancing astronaut efficiency and situational awareness during space missions. Although there have been numerous advancements in AR interface design for spacesuits, the challenge remains in how astronauts can effectively interact with AR systems in space environments. Traditional interaction methods, such as hand gestures, touchscreens, and voice commands, face significant limitations in the context of extravehicular activities (EVAs) and deep-space missions. Hand gestures, for instance, are impractical in bulky, pressurized gloves, where fine motor control is severely restricted. Touch-based interfaces, commonly used in modern spacecraft, become inaccessible during EVAs, as astronauts cannot directly operate screens while in a fully sealed spacesuit. Voice commands, though useful in some scenarios, are highly susceptible to interference from life support system noise, helmet acoustics, and communication delays, particularly in long-duration and deep-space missions.

Given these constraints, we are currently in the process of developing a more intuitive, hands-free interaction mechanism is needed to facilitate seamless communication between astronauts and AR-enhanced environments. Eye-tracking technology presents a promising alternative, as it enables precise, intent-driven interaction with AR elements without requiring physical input. By integrating gaze-based segmentation, real-time contextual overlays, and gaze-triggered actions, astronauts will be able to interact with AR systems efficiently and effortlessly, even while performing complex tasks in microgravity or extreme planetary conditions. This approach will ensure that AR interfaces are not just visual augmentations but also truly interactive and responsive tools, capable of adapting to astronauts' cognitive and operational needs in real time. To ensure efficient cognitive load management, the system

dynamically adjusts the level of detail based on gaze fixation duration and task complexity. By leveraging spatial awareness and historical user interactions, the VLM can anticipate potential queries, highlight relevant features, and provide context-sensitive explanations.

To further refine the interaction system, by leveraging VLMs to analyze historical and real-time gaze data, environment contextual data past actions, astronauts' intentions can be predicted. For example, once a high-value research sample is identified, a sample collection action is likely to follow. This allows for automated system adjustments, such as pre-loading relevant mission commands, suggesting optimal procedures, or prioritizing critical alerts. By integrating predictive interaction with LLM-powered automation, the system minimizes manual input, accelerates task execution, and enhances astronaut autonomy, making it a key advancement for long-duration deep-space missions [6].

While the proposed AR-embedded helmet system demonstrates promising capabilities in simulated EVA scenarios, several challenges remain before practical deployment in space missions. First, the accuracy and robustness of eye-tracking can be affected by extreme lighting conditions, such as high-contrast illumination on planetary surfaces or rapidly changing shadows within spacecraft environments. Second, optical and thermal constraints within the helmet visor may limit the placement and calibration stability of embedded eye-tracking and AR display modules. Third, integrating real-time computation of gaze-based segmentation and VLM inference into resource-constrained, radiation-hardened computing platforms suitable for space applications presents significant engineering hurdles.

This research has the potential to be a transformative step toward next-generation intelligent spacesuits that adapt dynamically to astronauts' needs. By merging eye-tracking, AR, SAM, and VLMs, this system aims to redefine human-machine interaction in space, facilitating safer, more efficient, and more intuitive space exploration.

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A Research Framework to Develop a Real-Time Synchrony Index to Monitor Team Cohesion and Performance in Long-Duration Space Exploration

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Abstract

As humanity prepares for long-distance space exploration, optimizing group performance, the ability of a group to achieve its goals efficiently, is critical. Astronaut crews will endure isolation, confinement, and operational stress, making group synchrony – the alignment of behaviors, emotions, and physiological states – a key factor in mission success. Synchrony influences team cohesion, performance, and resilience, necessitating effective crew management strategies. This paper proposes a framework for a real-time, unobtrusive index of group synchrony to support astronauts and mission control. Research indicates that team cohesion fluctuates in isolated environments, with reduced communication and interpersonal conflicts emerging over time. A system tracking synchrony could mitigate these issues, providing proactive support and improving remote management. Additionally, it could serve as a cognitive and physiological feedback tool for astronauts and a decision-making aid for mission control, enhancing well-being and efficiency. Our approach integrates behavioral and physiological synchrony measures to assess team cohesion and performance. We propose a multi-modal synchrony index combining movement coordination, communication patterns, and physiological signals such as heart rate, electrodermal activity, and EEG. This index will be validated across different tasks to ensure applicability across diverse mission scenarios. By developing a robust synchrony index, we address a fundamental challenge in space missions: sustaining team effectiveness under extreme conditions. Beyond space exploration, our findings could benefit high-risk, high-isolation teams in submarine crews, polar expeditions, and remote research groups. Our collaboration with the Centre National d'Etudes Spatiales, the Institut de Médecine et de Physiologie Spatiales, and the Toulouse University Hospital marks the first step, with experimental data collection starting this year. Ultimately, this research fosters more adaptive, responsive, and resilient teams for future space missions.

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1 Context

Human space exploration, particularly long-distance space exploration missions (LDSEM), represents one of the most challenging frontiers for human performance and adaptation. Among the many factors influencing mission success, group performance, defined as the ability of a group to achieve its goals efficiently, and synchrony, defined as the alignment of behaviors, emotions, and physiological states, are a critical area of focus, since it has been repeatedly shown that group synchrony and performance are positively associated. These concepts, encompassing how well a team collaborates, aligns in behavior, and maintains a shared cognitive and emotional state, are essential to the sustained operational efficiency and psychological well-being of astronauts. The unique demands of space missions – including isolation, confinement, extreme environmental conditions, and prolonged stress – highlight the need to understand and optimize group performance and synchronization to ensure the safety of operations, mission success, and crew health. The importance of group synchrony in LDSEM has not gone unnoticed. Indeed, several studies have focused on group dynamics and synchrony in teams that lived and worked together for different stretches of time, sometimes for prolonged periods of time and in conditions simulating those of LDSEM (i.e., Isolated and Confined Environments, hereafter ICE). A recent review and meta-analysis [5] summarised the findings of several analogue missions of different lengths and with and without ICE conditions. Bell and colleagues found that the relationship between cohesion, defined as the members' inclinations to forge social bonds and stick together, and performance was positive and significant for teams with the following characteristics: living and working together for shorter stretches of time, and not in ICE conditions. At variance with this result, this relationship was not as clearly observable in group living and working together for longer stretches of time, and in ICE conditions. This is probably related to the fact that cohesion, among other team dynamics, tended to fluctuate more for teams in ICE than for teams in non-ICE conditions [5], possibly masking existing associations. In line with this idea, two other major patterns were observed for ICE missions: communication between crew members and the mission control (MC) tended to sharply decrease with time and all missions reported at least one conflict among members at the mark of 90 days or by 40% of elapsed mission time [5]. The above mentioned meta-analytical results highlight the great positive impact that a continuous, real-time, unobtrusive index of group synchrony may have on LDSEM. Indeed, if cohesion, a proxy of group synergy, shows highly fluctuating levels, then tracking it at any given time will help to follow the group dynamic more closely. This could, in turn, allow for targeted interventions to restore synergy. The tracking of group cohesion might be even more critical if sensitive cooperative tasks, whose performance is associated to synchrony levels, are to be performed. When communications between crew and the MC decrease with time, the MC could benefit from a group synchrony index, since overt communication could dwindle to a level where inferring group synchrony would be impossible. Additionally, the synchrony index could help MC unmask latent or unresolved conflicts, and their after-effects, within the team and react by putting more emphasis on group synchrony during critical phases of missions. Finally, the crew itself could benefit from a measure of their current synchrony, especially because teams seem to be able to stabilize their level of synchrony when feedback about it is provided [11]. The current work details our group's efforts to develop the research framework needed to develop a real-time, continuous and unobtrusive index of group synchrony, to be used not only during LDSEM, but also in other contexts where tracking group synchrony is of essence. The paper is structured as follows: the first part focuses on the theoretical model of group performance, the second part focuses on group

synchrony, the third part proposes a theoretical framework relating group performance and synchrony, and the final part reports the proposed research framework while highlighting the questions that remain open.

2 Group performance

2.1 Input – mediating mechanism – outcome

Understanding group performance and synchrony requires a clear model of group functioning. Theoretical models play a crucial role in research, intervention design, and performance measurement. They help link physiological dynamics with team behavior, emotions, and outcomes. One of the most influential models in this field is the Input-Process-Outcome (IPO) model, originally introduced by McGrath [50] and later refined by Hackman and Morris [29]. The IPO model describes group functioning as a transformation of inputs – such as individual traits, team structure, and task constraints – through processes involving member interactions, leading to outcomes like goal achievement and perceived team effectiveness. Over time, researchers have expanded the model to include mediating mechanisms beyond physical behavior, such as shared cognition and motivation, leading to the Input-Mediating Mechanism-Outcome (IMO) framework [35, 45, 47]. Further refinements, like the Input-Mediating Mechanism-Outcome-Input (IMOI) model, recognize that outcomes can influence future inputs, particularly in long-term teams. While these models have shaped research on group performance for decades, contemporary perspectives increasingly view teams as dynamic, multi-level, and complex systems that may require alternative modelling approaches to better capture the intricacies of team interactions and performance over time.

2.2 Mathieu model

The Mathieu model was put forward in a seminal paper in 2017 [48] and sees the elements concurring to group performance as belonging to three main groups: 1) structural features, akin to environmental and task-related inputs in the IMOI models), 2) compositional features, akin to individual-based inputs, such as personality traits in the IMOI models, and 3) mediating mechanisms. However, rather than be seen as compartmentalized, the elements included in these 3 groups are seen as overlapping and co-evolving over time. Structural features are environmental and task-related, such as task scope and complexity that work towards group effectiveness [48]. Compositional features include elements pertaining to individual group members, such as IQ or personality traits, whose combination defines group-wise characteristics, such as the average IQ of the team or diversity, if heterogeneity is measured [46]. Finally, the mediating mechanisms are affective, behavioral, and cognition interdependent processes that convert inputs to outcomes. Such team processes can be conceived as transition, action, interpersonal processes, and emergent states that occur in varying episodic cycles [45]. Among the emergent states related to teams functioning, those deemed to be most important are cohesion, defined as the bond among team members [3], trust, and team potency, defined as the team's shared belief about their ability to accomplish relevant goals [63]. Meta-analyses of the relevant literature have shown that cohesion and team potency are positively related to team objective performance [34, 63], whereas trust is related to both objective team performance and affective outcomes [7, 16].

3 Synchronization

Group synchronization refers to the coordinated alignment of actions, emotions, and physiological processes among individuals. It occurs at behavioral (actions, communication), cognitive (thoughts, emotions), and physiological (brain and autonomic activity) levels, all of which are linked to group performance [18, 40, 43, 49]. Research has explored how these levels interact – whether physiological synchronization stems from behavioral or affective synchronization – but there is no consensus. Although causal mechanisms remain debated, studies have identified key relationships, such as the impact of task complexity on team physiology and the link between cohesion and behavioral synchrony. The following sections will describe these levels and their empirical connections.

3.1 Behavioral synchrony

Behavioral synchrony refers both to physical movements and actions and to communication. In light of the theoretical models described above, synchrony in these domains falls within the *mediating mechanism* group of features and can be thought of as akin to the *processes* in the IPO model.

3.1.1 Measures of behavioral synchrony

Behavioral synchrony can be assessed with both manual and automatic methods. As for manual methods, annotation of video recordings of team members performing the assigned task has been used. Trained observers assess whether a behavioral or communication interaction is present or absent among dyads in the team and within windows of fixed time [25]. These types of methods have been validated in empirical studies [25, 68], but are not compatible with the real-time tracking of synchrony levels. However, automatic methods have been developed, such as measuring the association between team members' movements, estimated using video-based optical flow [15, 54, 55], or measured using accelerometers worn on the effectors involved in the completion of the task [12]. Although this family of measurement can be used for real-time synchrony tracking, it has some limitations. For one, synchrony measures based on movement estimation from video-based optical flow are better suited for tasks where participants stay relatively still. Indeed, involuntary and automatic body and posture adjustments related to non-verbal communication are measured. As such, these measures are adapted for tasks such as brainstorming or decision making, where team members are seated, rather than to tasks demanding complex movements (e.g., assembling a Lego set). At variance, features based on measuring the movements of the effectors used for task completion are intrinsically task-specific: it is necessary to know in advance the effector(s) that will be used for task completion and the best placement for the accelerometers. As such, these measures are hard to generalize across tasks. As for communication synchrony, automatic methods have also been developed based on the similarity of words used by team members, detected by speech recognition algorithms [26] or by measuring recurrent patterns in the temporal structure of the conversation [23]. These methods are compatible with real-time detection and have the intrinsic advantage of being generalizable across tasks, as long as communication between team members is allowed and relevant. However, they are resource-intensive from an operational viewpoint, as each team member should be equipped with a microphone, and the speech recognition algorithm and similarity assessment are computationally intensive.

3.1.2 Behavioral synchrony and group outcomes

Behavioral synchrony is closely linked to group outcomes, influencing relationship formation, cohesion, rapport, and performance. [67, 28, 25, 22, 59]. Studies show that behavioral synchrony is related to interpersonal liking [55], while its absence correlates with conflict [54]. Experimental manipulations increasing synchrony have improved in-group cohesion [66]. However, its impact on performance is complex – while synchrony benefits teamwork in some contexts, it can hinder performance in cognitively demanding tasks. For instance, high synchrony in complex tasks like construction or interpersonal perception can reduce effectiveness, possibly due to an emphasis on harmony over critical discussion. Conversely, synchrony defined by leadership-followership complementarity can enhance group efficiency [22]. Communication-based synchrony also correlates with performance and social outcomes such as rapport and empathy [24, 23, 26, 68, 36]. However, its effects vary with context. In psychotherapy, vocal pitch synchrony has been negatively associated with therapeutic alliance, while language similarity benefits short-tenure groups but may harm long-term teams by fostering off-topic discussions [32]. The nature of the task also matters: mimicry-based measures, such as measures of similarity in word choice and speech pattern, align more with social bonding, whereas measures of complementarity in communication (e.g., turn-taking) better predict analytical performance [17, 36]. Overall, while behavioral synchrony is crucial for group functioning, its impact on performance depends on task type and complexity and team characteristics (e.g., team tenure).

3.2 Cognitive synchrony

Cognitive synchrony can be conceived as the ensemble of shared cognitive (e.g., transactive memory system, shared cognitive models, etc.) and affective (e.g., psychological safety, cohesion, trust, etc.) processes emerging from team interaction.

3.2.1 Measures of cognitive synchrony

When examining the relevant literature, it becomes clear that this is the most complex level of synchrony to measure, since by definition, cognitive functions and affective states are not directly observable. It is, thus, not surprising that synchrony in cognitive processes is usually inferred from the other levels of synchrony, behavioral or physiological, albeit paper-and-pencil methods have been proposed (e.g., for the transactive memory system [44]). Cognitive synchrony in groups can be assessed by measuring similarities in demographics, psychological traits, and cognitive styles, whereas diversity is quantified through the variability in these measures. Affective synchrony is usually measured using questionnaires or other self-reporting methods. Since all of these measures are based on questionnaires, they are clearly not adapted to real-time measurement. Although some of them are shorter and could be presented auditorily during operational tasks, this would have the obvious disadvantage of diverting attention from the task and negatively impact the ecological validity of the study. Nonetheless, questionnaires are considered the "gold standard" when it comes to cognitive synchrony. As such, any experimental protocol devised to validate unobtrusive methods to measure cognitive synchrony will still need to include one or more questionnaires that will be used as ground truth.

3.2.2 Cognitive synchrony and group outcomes

Elements related to cognitive synchrony have been repeatedly shown to be associated with group outcomes, both in terms of objective and affective outcomes. Average intelligence across group members and average scores of conscientiousness, agreeableness, and extraversion are related to objective performance [4, 19]. Similarly, functional diversity, defined as team members coming from different functional areas or backgrounds, is positively related with objective performance [6]. In terms of cognitive synergy, both the transactive memory system (TMS) and shared cognitive models have been found to be associated with group performance [2, 47], with TMS also being associated with self-reported measures of team member satisfaction [2]. Meta-analytical analyses of studies conducted in long-term employment groups in industry and commerce have shown that psychological safety and trust are related to both objective group performance and affective outcomes such as commitment and satisfaction [16, 21]. As for cohesion, although there is a consensus on the fact that cohesion is positively related to objective performance, the findings about affective outcomes are not as clear [3, 8, 34]. Although there is a vast literature on the association between cognitive synchrony and group outcomes, it is worth mentioning that the reported studies and meta-analyses are based exclusively on ad hoc groups recruited for the duration of an experiment, making them hardly comparable to groups of astronauts spending many months together, or on long-term groups from private firms or governmental agencies, environments where the stress and demands endured are not comparable to those experienced by astronauts. Even for groups recruited in higher stress environments, such as firefighter departments or first responder units, there is a lack of generalizability of the findings to astronauts, since these groups do not experience an isolated and confined environment. How the specific interaction of long-term tenure, highly stressful, and isolated and confined environment may influence the relationship between cognitive synchrony indices such as cohesion and objective performance is still an open question.

3.3 Physiological Synchrony

Physiological synchrony refers to the interdependent structure amongst physiological signals of group members that can take the form of changes in magnitude, frequency, and phase that occur at the same time within two or more team members, but also to complementary changes that are time-locked amongst group members. In the current paper, when we refer to physiological signals, we include both signals from the periphery, usually thought to be related to autonomic nervous system activation (i.e., heart rate, respiration, electrodermal activity), and signals pertaining to the central nervous system (i.e., electrical activity measured using electroencephalography). Overall, it should be noted that a recent meta-analysis [49] reported significant meta-analytical associations between physiological synchrony measures, based on sympathetic activity, parasympathetic activity, or both, and affective outcomes. However, the direction of the association was different between measures, being positive for sympathetic and combined measures, and negative for parasympathetic measures. The highest meta-analytical correlation, found for parasympathetic activity, was around 0.2, interpretable as a very weak correlation. A positive meta-analytical association was also found between physiological synchrony and measures of group performance ($r = 0.26$) [49]. It should be taken into consideration that because of the relatively low number of papers included in the meta-analysis, measures derived from different signals were analysed together. Moreover, since the meta-analysis included studies using different task types, the variability of the association between synchrony and performance as a function of task type may have deflated

the magnitude of the correlation. Note that the studies included in the meta-analysis by Mayo and colleagues (2021) were conducted in laboratories and not in simulated or real space conditions. As such, some of the results may not hold in such conditions. Physiological measures of synchrony have the appealing characteristics of being unobtrusively recordable (i.e., with no effect on the task and without the participant noticing), continuously and in real-time. Different physiological sensors have different usability profiles in relation to their size, their resilience to noise, and the easiness of their analysis.

3.3.1 Heart rate

Heart rate and heart rate variability reflect the balance between the sympathetic and parasympathetic nervous systems. Physiological synchrony in heart rate has been observed in various tasks, including cooperative gaming, drumming, decision-making, and military exercises [28, 25, 51]. Studies link heart rate synchrony to both performance and affective outcomes, although the relationships are complex and the direction of the association is sometimes inconsistent [28, 30, 31, 62, 64, 27, 38, 52]. Heart rate is easily measured with photoplethysmography (PPG) in wearable devices, whereas electrocardiography (ECG) offers higher precision but requires electrodes in contact with the skin. Smart garments with embedded ECG sensors provide new operational possibilities. Heart rate measurements, both from PPG and ECG, have been shown to be reliable in microgravity conditions.

3.3.2 Electrodermal activity

Electrodermal activity (EDA) reflects skin electrical variations controlled by the sympathetic nervous system, making it a key measure of stress, arousal, and affective states. EDA-based synchrony has been studied in various group tasks, including teleoperation, creative problem-solving, and collaborative programming [31, 37, 61]. It is more consistently linked to affective outcomes than objective performance, although findings on directionality vary [9, 10, 14, 37, 39, 53]. Most studies report positive associations, although some find negative or null results. EDA is traditionally measured using gelled electrodes on fingers or palms, though newer wearable dry-electrode solutions reduce noise and improve usability in dynamic tasks [56, 57]. To the best of our knowledge, there are no formal reports of tests of EDA signals in microgravity, however the physiological mechanisms responsible for this signal, (i.e., the activity of sweat glands in the skin) are unlikely to be affected by microgravity.

3.3.3 Electroencephalography

Electroencephalography (EEG) measures the electrical activity of the brain, specifically the sum of post-synaptic potentials of pyramidal neurons in the neocortex. The emergence of "hyperscanning" [20] has allowed for the simultaneous recording of brain activity from two or more individuals, enabling the study of inter-brain synchronization (IBS). IBS is thought to reflect how brain activity becomes synchronized with another individual, much like how brain activity synchronizes with external stimuli, such as a flickering light or a musical note. A recent meta-analysis [60], focusing on laboratory studies, categorizes IBS research into three areas: association with input factors, association with mediating mechanisms, and association with output. The study found moderate associations between IBS and input factors. The analysis also revealed a moderate association between IBS and mediating mechanisms, particularly stronger in turn-taking tasks compared to synchronization and free tasks. However, the association between IBS and output – measured in terms of objective

performance – was weak. Notably, many studies that focused on objective performance showed negative associations with IBS. This could explain the weaker meta-analytical association between IBS and objective performance and point to the fact that the IBS quantification method and/or the type of task can influence the direction of the association. EEG-based IBS research has primarily focused on controlled laboratory tasks with limited ecological validity, such as simple movement tasks [41], joint attention to visual stimuli [42], and speech coordination [1]. However, more recent research has successfully applied "hyperscanning" in ecological tasks. For instance, Toppi et al. [65] explored IBS between pilot crews during a simulated flight, and Hu et al. [33] examined IBS during cooperative and competitive decision-making tasks. Studies like these are particularly valuable as they involve real-world tasks and the use of portable EEG systems, such as dry electrode setups that do not require conductive gel. All of the aforementioned studies found a positive relationship between IBS and objective performance [41, 42, 1, 65, 33]. Despite its potential, EEG-based IBS faces several limitations. Although some studies use smaller, portable, dry electrode systems, most still require at least 14 electrodes, complicating operational adoption. Additionally, EEG data are highly susceptible to environmental and physiological noise, making real-time application challenging. Aggressive preprocessing and semi-automatic de-noising procedures are typically employed, but human intervention for visual inspection remains necessary. Finally, the various metrics used to quantify IBS have not been systematically compared, making it difficult to select the most reliable and effective method. These challenges have delayed the real-time use of EEG-based IBS for tracking group performance. In terms of its use in microgravity, EEG measures have been shown to be robust under microgravity conditions, although specific changes relative to terrestrial recordings have been identified [58, 13].

4 Relationship between group performance and synchrony

Based on the relevant literature on group performance and synchrony, we propose a model of the relationship between these two concepts. This model is meant to clarify the relationship between different sub-elements of group performance and group synchrony in order to inform the experimental framework necessary to the development of a real-time measure of synchrony that is meaningful for group performance. The model is presented in figure 1.

Group performance output, including both objective and affective outcome of teamwork, is determined by how the input is modified by the mediating mechanisms taking place within the group. In turn, the output can become input again, as material production of the group and the starting point of the next iteration. Affective outcomes can feed back into the loop, or influence the mediating mechanisms, for example by modifying shared mental models or by increasing group potency. As for synchrony, the different levels at which it can be observed (i.e., cognition, neurophysiology and behavior) all interact with each other. Elements of group performance and levels of synchrony observation can influence each other. The input needed for group performance can influence cognition and neurophysiology (e.g., compositional features such as personality traits or intelligence influence cognitive synchrony; perceptual features from task-related stimuli influence neurophysiological synchrony). Additionally, cognitive and behavioral synchrony are closely associated with the mediating mechanisms that are necessary to transform the input into the output of the group performance. Finally, although in this model, neurophysiological synchrony does not interact directly with elements of group performance, it can influence the mediating mechanisms via its relationship with both cognitive and behavioral synchrony. Overall, there is a circular relationship between

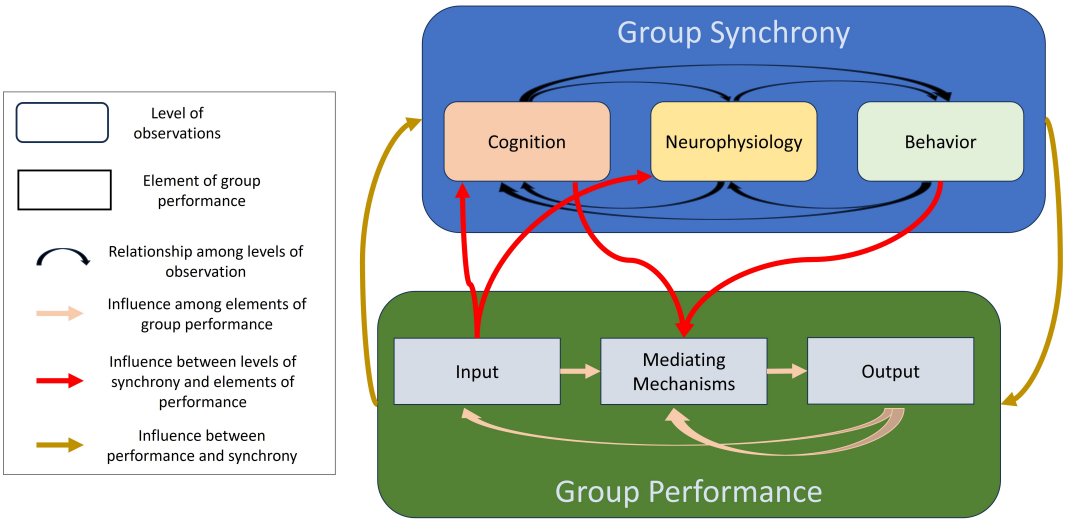

Figure 1 Relationship between group performance and group synchrony.

group synchrony and group performance. Group synchrony influences group performance and vice-versa. Note, however, that this influence is not necessarily positive: while positive outcomes (e.g., attaining team goals or increasing trust and cohesion) can increase synchrony, negative outcomes (e.g., not attaining team goals and the associated stress) can decrease synchrony. In turn, the influence of synchrony on group performance varies as a function of the task demand: as an example, tasks demanding divergent thinking can be hindered rather than facilitated by high levels of group synchrony. However, affective outcomes, such as trust or cohesion, and synchrony seem to have a more straightforward relationship: when the latter increases, the former increases too. Among the different elements of this combined model, some are more easily measurable than others. Specifically, we argue that while mediating mechanisms (the element most closely related to output) cannot be directly measured in real-time, as they are mainly cognitive in nature, two elements of synchrony, namely behavioral and neurophysiological synchrony, can be measured in real-time. They can also be leveraged as an index of important mediating mechanisms (such as cohesion) and ultimately, predict group performance. This led us to the experimental framework that will be presented in the following section. On the basis of this theoretical model, three families of study on this topic can be defined. First, "type 1" research: *the group performance focused studies*. These are studies that aim to better understand the relationship between the elements pertaining to group performance strictly speaking (i.e., the pink arrows within the green box in figure 1). "Type 2" research is *the inter-elements studies*, composed by studies aiming at better understanding the relationship between specific elements of group performance and specific observational levels of synchrony (e.g., how input influences cognitive and neurophysiological synchrony or how cognitive and behavioral synchrony influence the mediating mechanisms; see the red arrows in figure 1). Finally, "type 3" research is *the performance-synchrony relationship studies*. These are studies that look at the association of synchrony (measured with indices pertaining to specific levels of observation or with composite indices) and group performance, and specifically, group outcome, under different conditions (golden arrows in figure 1).

5 Research framework

The global research framework that we propose is schematically presented in figure 2.

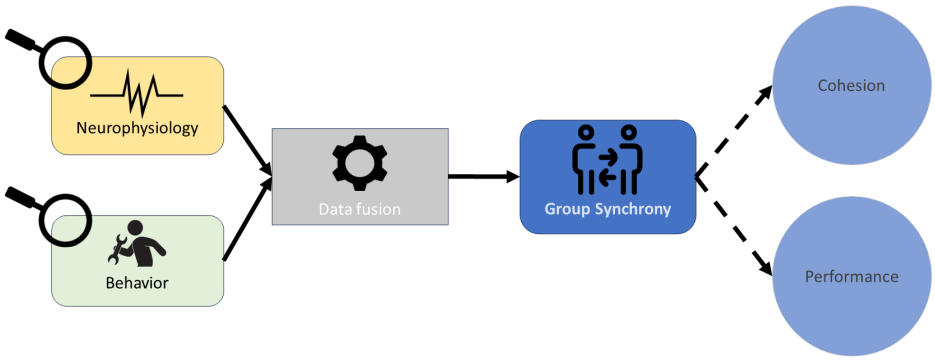

Figure 2 Schematic representation of the research framework for the development of a group synchrony index.

The main idea is to measure neurophysiological and behavioral synchrony in real-time within teams. Neurophysiological and behavioral indices of synchrony would then be merged using data fusion techniques in order to obtain a single multi-source group synchrony index, predictive of cohesion and, in a task-dependent manner, of performance (see below). This synchrony index may then be shared with the team itself, as feedback useful for maintaining the desired level of cohesion and for alerting when critical states (e.g., extremely low levels of cohesion) are nearing. This index would also be used by Mission Control or any other long-distance managing entity, to inform the group about managing strategies, task assignment, etc. Based on the plethora of measures used to assess neurophysiological and behavioral synchrony, and on the complex relationship between these features and affective and objective outcomes of teamwork, it is necessary to first select the best measures and to characterise their relationship with cohesion and performance during different task types. In particular, it is important to observe how synchrony measures relate to cohesion and performance during tasks where synchrony is the overt aim, during "convergent tasks" (i.e., tasks where synchrony is not the overt aim, but is expected to improve performance), and during "divergent tasks" (i.e., tasks where synchrony and cohesion can have a negative impact on performance). Within the taxonomy of studies described above, this study belongs both to the inter-elements studies and to the performance synchrony studies. Indeed, we will focus on specific levels of observation of synchrony, trying to associate them with a mediating mechanism (i.e., cohesion) but also to the overall group performance, and specifically, the objective outcome of teamwork, under different conditions (i.e., different task types). The framework that will be used to develop experimental protocols for the measures selection phase is outlined in figure 3.

In order to characterise and eventually select the best features, we propose the following: the experimental protocol will include three different tasks. For each of these tasks, cohesion and objective performance will be measured. One task will have synchrony as its overt aim: synchronous drumming (i.e., drumming in time with a metronome) has been repeatedly shown to induce behavioral and physiological synchrony and to increase cohesion among team members. This task can be conceived as a validation task, useful for testing the ability of the selected features to measure synchrony, and its association with performance and cohesion,

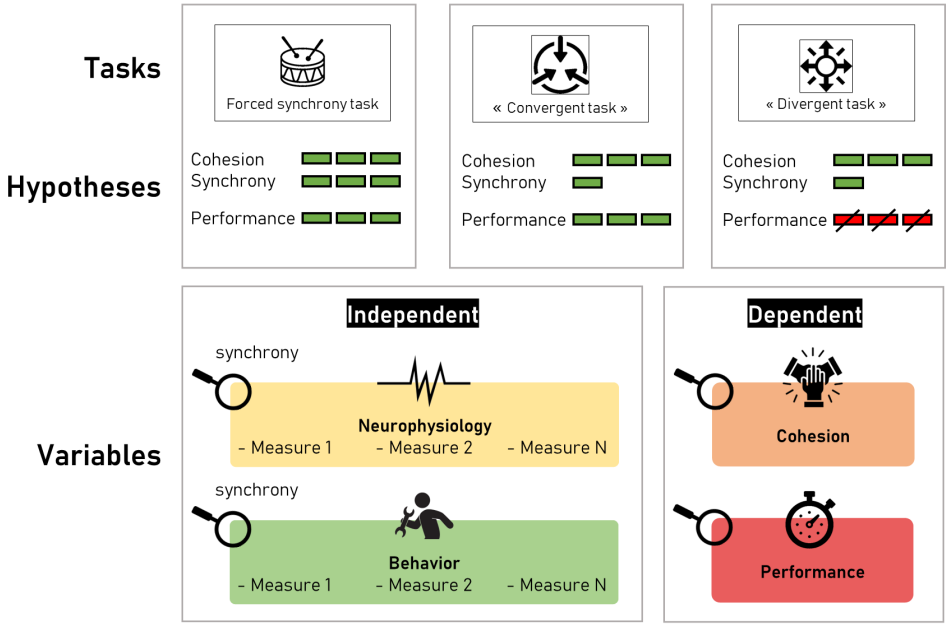

Figure 3 Schematic representation of the measures' characterisation and selection step.

when these latter are known to be present. Another task will be a "convergent task", such as decision making or a simulated hiring task [33]. The third task in the protocol will be a "divergent task", a task where an excess of synchronization and cohesion can hinder the performance, as divergent thinking among team members is necessary, such as the creative phase of brainstorming. The measure of synchrony that will be included in this first step remains an open question. On the basis of the literature, we are aiming at including a movement-based and a communication-based measure of behavioral synchrony, respectively an optical flow-based and a language style matching-based measure. As for the specific metric of synchrony to use (e.g., multivariate recurrence, cross-correlation, phase coherence), this is still open to debate. As for neurophysiological synchrony, we are aiming to record heart rate, EDA, and EEG data. For neurophysiological synchrony, we are planning to include several indices of synchrony, and specifically, at least one linear index (e.g., cross-correlation) and one frequency-based index (e.g., frequency or phase coherence), but the specific indices to use are yet to be identified.

6 Conclusion

In this paper, we have presented a literature review about group performance and group synchrony. Based on this literature review, we have presented an experimentally oriented theoretical model of the relationship between elements of group performance and of group synchrony. We then used this model to inform a research framework to develop a real-time, continuous index of group synchrony that can be used as a proxy for cohesion and, eventually, to predict group performance. We argue that such an index could be extremely useful in the context of space missions, and especially for long-distance missions. Indeed, the relevant literature suggests that cohesion is especially fluctuating for crews spending long stretches of time in isolated and confined environments. Moreover, these crews tend to communicate

less with mission control as time-on-mission increases, and they tend to experience at least one conflict within 90 days of a given mission. All this evidence suggests that an index of group synchrony, that is able to track group cohesion and to predict group performance, may be equally useful for crew members and for mission control. It could serve as feedback for the crew to increase cohesion levels and as a cue for mission control to help with personnel management. Such a group synchrony index could, of course, be helpful in other contexts where crew members have to live and work in isolated and confined environments for long stretches of time. Clearly, the applicability or real-time synchrony assessments would depend on specific mission conditions. For astronauts, the index could always be available in real-time, if the necessary calculations are made within the spacecraft, but mission control would lose the ability of having proper real-time assessments with the spacecraft's increasing distance from Earth. However, we argue that even in the absence of a real-time assessment, a synchrony index could provide valuable information to mission control and alert them about anomalies in synchrony levels. At the time of writing, the team is finalizing the experimental protocol of the first step of our research plan: the characterization and selection of behavioral and neurophysiological synchrony indices and their relationship with cohesion and group performance, under different task types. The data collection campaign is planned to start in the current year, in collaboration with the National Centre for Space Study (CNES), the Institute for Space Medicine and Physiology (MEDES) and the Toulouse University Hospital.

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Monitoring the Structural Health of Space Habitats Through Immersive Data Art Visualization

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Abstract

As humanity advances toward long-term space habitation, traditional SHM systems – reliant on abstract data representations – struggle to support rapid decision-making in extreme environments. This study addresses this critical gap by introducing an engineering-art-human factors framework that transforms SHM through immersive data-art visualization. By integrating sensor networks and machine learning, structural data (stress, vibration, deformation) is converted into intuitive visual languages: dynamic color gradients and biomimetic morphologies leverage perceptual laws (e.g., Weber-Fechner) to amplify critical signals. Multimodal interfaces (AR, haptic feedback) and natural elements mitigate cognitive load and psychological stress in confined habitats. Our contribution lies in redefining SHM as a synergy of precision and intuition, enabling "at-a-glance" assessments while balancing functionality and human-centric design. The urgency of this research stems from the inadequacy of conventional systems in extreme space conditions and the growing demand for astronaut safety and operational efficiency. This framework not only pioneers a sustainable monitoring paradigm for space habitats but also extends to terrestrial high-risk infrastructure, demonstrating the necessity of interdisciplinary innovation in extreme environments.

2012 ACM Subject Classification Human-centered computing → Human computer interaction (HCI); Human-centered computing → Haptic devices; Human-centered computing → Visualization systems and tools

Keywords and phrases Structural health monitoring, space habitats, immersive visualization, human-centered design, interdisciplinary innovation

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1 Introduction

Human space exploration is transitioning from brief missions to sustained extraterrestrial habitation, necessitating robust Structural Health Monitoring (SHM) systems for astronaut safety and mission sustainability [41]. Space habitats endure extreme environmental stressors including microgravity-induced material fatigue, thermal cycling (−150 °C to 120 °C), cosmic radiation, and hypervelocity micrometeoroid impacts [9, 4]. While sensor networks and AI-driven models have improved data analysis, traditional technical visualizations (heatmaps, spectrograms) impose excessive cognitive load during critical operations [47, 55], creating an urgent need for intuitive interpretation frameworks.

Integrating art and engineering holds significant transformative potential, creating new avenues for innovation across multiple domains, including dyslexia support tools [17], interactive immersion systems [52, 21, 18], and advanced data visualization techniques [20, 44, 19]. Prior studies like [50] demonstrate visual abstraction's value for data interpretation, yet space applications remain limited by insufficient robustness. This study addresses these gaps through an "engineering-art-human factors" framework combining high-fidelity sensors (strain gauges, acoustic sensors) with LSTM-based anomaly detection. Structural data transforms into artistic visual metaphors via generative AI and fluid dynamics, using color gradients (green-to-red) and biomimetic deformations that amplify perceptual salience through Weber-Fechner Law principles [3, 29].

Beyond visualization, the framework incorporates multimodal interaction and psychological adaptability. Haptic feedback via force-sensing gloves and AR interfaces compensates for visual limitations, while naturalistic elements (e.g., fluid animations) mitigate space-induced isolation [9]. Here, aesthetic components serve as cognitive catalysts rather than decorative elements.

This research addresses three core questions: (1) How artistic visualization enhances structural data interpretation; (2) Optimal techniques for conveying critical information; (3) Immersive visualization's impact on high-pressure decision-making. Methodologically, it integrates sensor networks, machine learning, and immersive platforms to develop adaptive visualizations tested for cognitive load reduction. By bridging engineering precision with artistic intuition, this work pioneers human-centered SHM for sustainable space exploration.

2 Background and Related Work

Structural Health Monitoring (SHM) is critical for aerospace systems, where sensor networks (strain gauges, acoustic sensors, thermal cameras) detect structural anomalies [16]. Recent advances include AI-driven predictive models [4] and quantum-enhanced sensing [8, 5], improving anomaly detection accuracy. Distributed fiber-optic systems now achieve sub-millimeter resolution in lunar habitat mockups [41]. However, these technologies prioritize data acquisition over human cognitive limitations in high-stress environments.

Space habitats present unique challenges: microgravity alters material fatigue mechanisms [10], thermal cycling (-150°C to +120°C) induces microcrack propagation [36], cosmic radiation degrades composites, and micrometeoroid impacts pose catastrophic risks [15]. Conventional SHM systems struggle under these conditions, with piezoelectric sensors losing sensitivity to radiation [6] and strain gauges showing thermal drift [51].

Current SHM interfaces (heatmaps, dashboards) are ineffective for astronauts. 2D visualizations increase decision latency by 30% during emergencies [50], while microgravity impairs spatial mapping of abstract data [22, 37]. High stress further degrades working memory [49], and 68% of ISS astronauts report interface-induced stress from cluttered

displays [35]. Emerging solutions include naturalistic designs (fluid animations, adaptive soundscapes) [23] and multimodal interfaces (AR with haptic gloves) that improve task accuracy by 40% [31]. Data-art approaches like stress-to-weather mappings [45] and GAN-generated 3D sculptures [54] show promise for intuitive interpretation.

Despite progress, three gaps persist: (1) Environmental robustness issues (AR degradation under radiation [26], sensor thermal drift [28]); (2) Superficial artistic integration, with 80% of interfaces perceived as sterile [14]; and (3) Insufficient interdisciplinary validation, particularly for perception-action coordination in microgravity [30]. Proposed solutions include radiation-hardened diamond sensors [7], bioluminescent data metaphors [54], and federated learning for distributed processing [13], but these lack unified testing.

3 System Design

Our SHM utilizes MR framework that integrates VR and AR into a head-mounted display embedded within the astronaut's spacesuit helmet (a brand-new MR headset). It is designed to enable astronauts to efficiently monitor, analyze, and respond to environmental and structural conditions within extraterrestrial habitats. It addresses three primary objectives at this stage: Environmental scanning, task guidance and problem-solving, and extraterrestrial environmental analysis and agricultural cultivation guidance. Besides the general MR control by hand, our SHM incorporates eye-tracking technology for hands-free operation. Users interact with the interface by focusing their gaze on specific icons or objects for a predefined duration (e.g., 3 seconds). This feature enables intuitive and efficient navigation, even in high-stress scenarios. Additionally, it adapts dynamically to user preferences, offering multimodal feedback through holographic visuals, audio prompts, and haptic signals.

3.1 Environmental Scanning

The environmental scanning module transforms complex spatial and structural data – including radiation levels and magnetic fields – into intuitive visualizations that enhance astronaut situational awareness and decision-making [24]. Utilizing a progressive disclosure approach, the system guides users through structured environmental analysis. Upon entering a new space module, it initiates a full scan to identify objects, equipment, and hazards, generating a semi-transparent 3D map that reveals spatial relationships and concealed areas (e.g., cabinet contents or structural supports). This framework enables safe navigation and interaction within the habitat [25].

The scanning sequence progresses through four phases: (1) An instructional interface establishing cognitive frameworks for spatial analysis (Fig. 1a); (2) Processing visualization with electromagnetic propagation indicators (Fig. 1b); (3) Spatial mapping using biomorphic wireframes highlighting infrastructure and anomalies (Fig. 1c); and (4) Interactive exploration with gaze-directed querying (Fig. 1d). This phased approach balances information density with cognitive accessibility through volumetric visualization.

Design principles integrate perceptual psychology: Semi-transparency maintains environmental context while overlaying critical data. A wavelength-based chromatic schema uses cool-spectrum colors (460-490 nm) for normal conditions and warm-spectrum (570-620 nm) for alerts [48, 40]. Persistent peripheral menus provide access to analytical tools – compositional analysis, atmospheric monitoring, structural assessment, and biological evaluation – via perceptually optimized icons. This methodology reduces cognitive load while strengthening spatial comprehension in artificial environments.

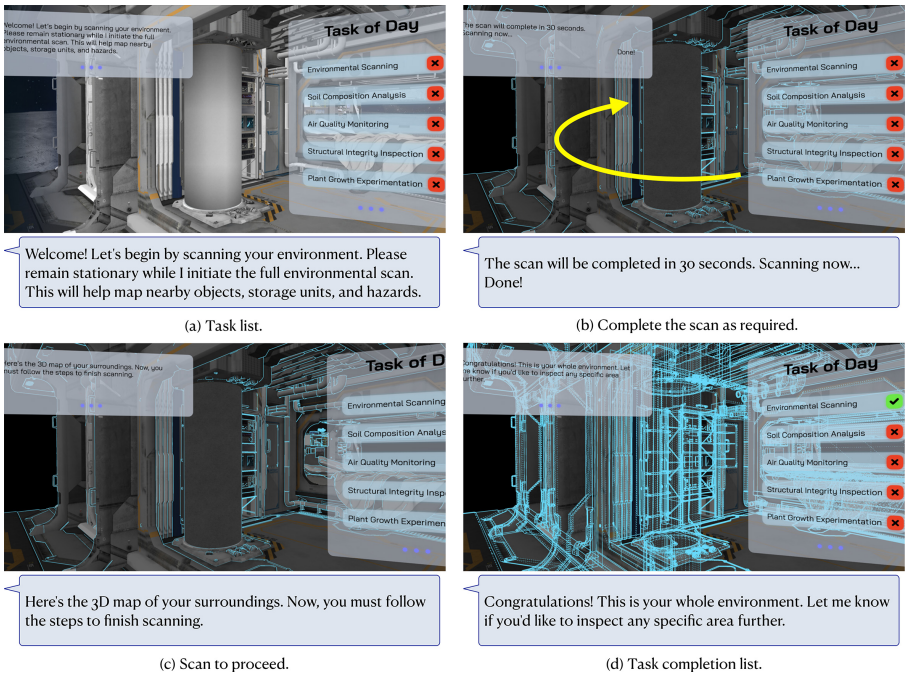


Figure 1 The display of the scanning process of the astronaut's living space.

3.2 Task Guidance and Problem-Solving

This module provides real-time emergency response capabilities through adaptive visual guidance. Upon detecting structural anomalies or equipment failures, the system immediately alerts astronauts via mixed-reality (MR) visual and auditory cues (Fig. 2). It generates comprehensive response frameworks including damage assessment, resource identification, and procedural instructions. For example, during pressure breaches, the system locates the damage, identifies repair equipment, and visualizes repair procedures directly in the astronaut's field of view.

The guidance interface employs four integrated visualization elements: (1) Spatial navigation markers (red pathfinding lines) directing astronauts to damage locations; (2) Equipment identification thumbnails with color-coded borders (green=available, red=unavailable); (3) Step-by-step repair protocols overlaid on damaged components; and (4) For unprecedented scenarios, AI-generated visual instructions derived from real-time environmental analysis. This phased approach transforms complex emergencies into executable workflows.

Visual design prioritizes critical information during crises through chromatic and spatial hierarchies. Structural stress models visualize failure cascades as propagating patterns to communicate urgency. Pre-established protocols anchor spatially to relevant components, while novel scenarios trigger AI-generated solutions transmitted as simplified visual instructions. This approach enhances crew autonomy during deep-space missions where Earth communication delays prevent real-time support.

3.3 Extraterrestrial Environmental Analysis and Agricultural Cultivation Guidance

Building on regolith cultivation research [12, 46, 34, 43], our SHM transforms environmental data into agricultural insights through a three-phase workflow. The system initiates with mandatory environmental assessments: soil analysis, atmospheric verification, and radiation

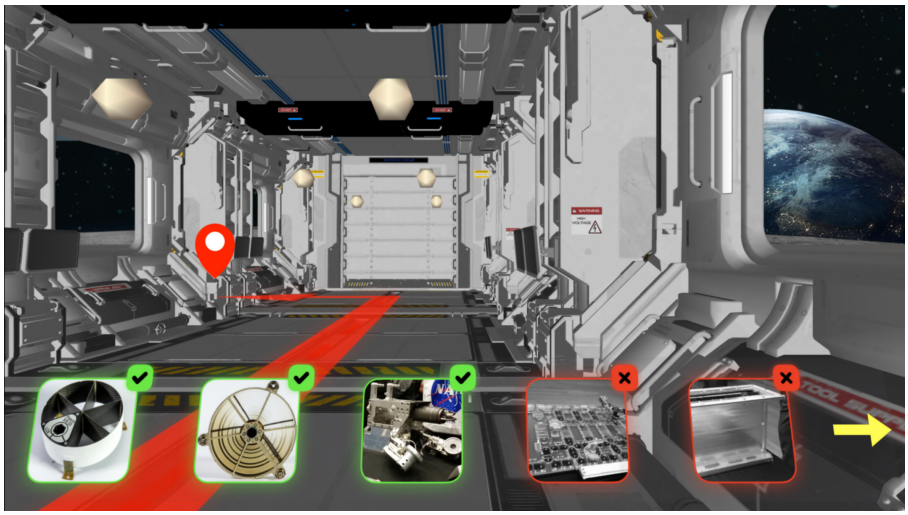


Figure 2 The display of guidance for emergency situations.

measurement. Astronauts complete these tasks using directed sensors, with traffic-light indicators (red→green) providing real-time completion feedback (Fig. 3a). This ensures comprehensive data collection before agricultural planning.

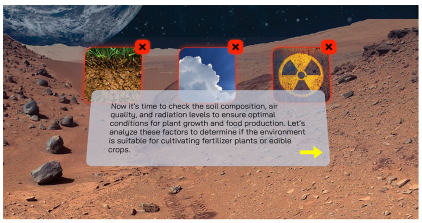
The analysis phase employs algorithmic evaluation against a botanical database, generating viability percentages for various crops. As shown in Fig. 3b, the interface displays primary crop options (e.g., 82% viability for tomatoes [38]) with detailed specification cards showing soil, atmospheric, and radiation requirements. This enables data-driven crop selection without specialized expertise.

Growth visualization (Fig. 3c) maps the complete phenological progression from sowing to maturity. Biomimetic illustrations depict developmental stages (germination, seedling, flowering, fruiting, maturity), while critical parameters display optimal ranges: diurnal temperatures (20-25°C light/15-20°C dark), pH (5.5-6.5), and CO_2 levels (0.1%-0.5%) [27]. Current stage indicators and temporal projections ("Germination: 10-15 days") support cultivation management.

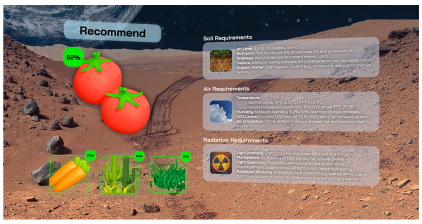
This integrated approach – environmental assessment, algorithmic recommendation, and growth visualization – enables non-specialists to implement sustainable food production. By transforming complex agronomy into intuitive workflows, the system enhances mission self-sufficiency in resource-constrained space habitats.

4 Visualization Methods

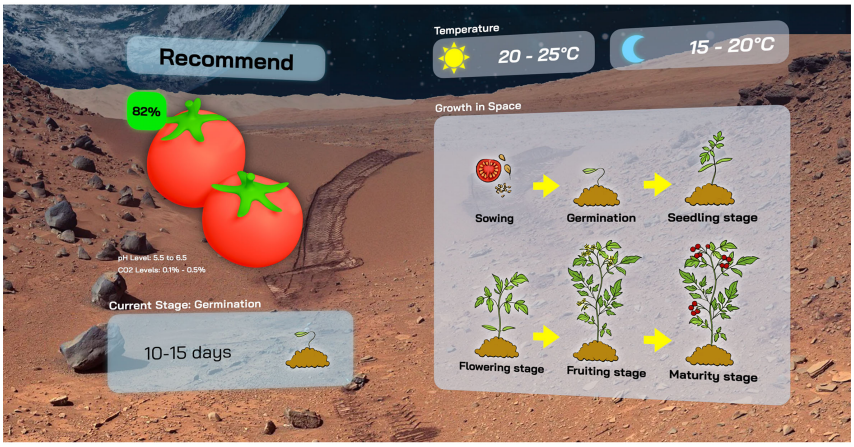
The SHM's visualization methods prioritize intuitive and artistic representation of complex data, ensuring that astronauts can quickly comprehend critical information without excessive cognitive load. Beyond the core visualizations for standard monitoring, we have developed specialized visualization techniques for emergencies, unpredictable anomalies, and varying operational conditions, including low-light environments, radiation storms, and communication blackouts.



(a) Check the condition of soil, air, and radiation.



(b) Show recommended plant/fruit.



(c) Predicted growth visualization.

Figure 3 The display of the environmental analysis interface guidance.

4.1 Core Visualization Techniques

Core visualization techniques incorporate adaptive parameters responsive to environmental conditions, user preferences, and mission context (see Table 1).

4.2 Specialized Visualization Methods

Beyond the above standard operational visualizations, our system adapts to challenging scenarios through specialized techniques:

1. During emergencies, the system shifts to high-contrast monochromatic representation with exaggerated depth cues to maintain legibility under stress and potential visual impairment. Information priority is automatically recalibrated, with critical safety data enlarged while peripheral information is minimized or temporarily hidden.
2. For unpredictable anomalies that fall outside standard detection parameters, the system employs "uncertainty visualization" techniques, including probabilistic boundary rendering, confidence-weighted transparency, and multivariate comparison indicators that highlight deviations from baseline environmental norms without presupposing the nature of the anomaly.
3. In challenging environmental conditions, visualization adapts dynamically. During low-light operations, the system shifts to a reduced-spectrum palette emphasizing blues and greens to preserve night vision; During radiation events, the system implements temporal redundancy (repeating critical information at intervals) to compensate for potential cognitive disruption; During communication blackouts, visualization complexity automatically reduces to prioritize system longevity and essential functions.

Table 1 Core Visualization Techniques.

Visualization Type	Application	Visual Implementation	Cognitive Benefit
Dynamic 3D Visual Metaphors	Structural integrity monitoring	Color gradients (green-to-red) for stress mapping with pulsating intensity proportional to criticality	Intuitive threat assessment with temporal urgency cues
	Environmental gas composition	Fluid animations resembling bioluminescent flows with density indicating concentration levels	Pattern recognition through biomimetic visual metaphors
	Soil composition analysis	Layered concentric spheres with segment size representing proportional composition and texture indicating granularity	Spatial comprehension with hierarchical organization
	Radiation exposure mapping	Heat-map overlays with contour lines indicating exposure boundaries	Spatial risk assessment
	Water resource tracking	Flowing particle systems with color intensity reflecting purity levels	Intuitive quality assessment
Alert Systems	Emergency notifications	Pulsating outlines with directional indicators and intensity synchronized to heart rate monitoring	Attention capture with physiological alignment
	Threshold violations	Color saturation intensification with harmonic oscillation patterns	Perceptual prioritization through dynamic contrast
	Critical warnings	Symbolic motion patterns (expanding concentric rings) with acceleration proportional to urgency	Subliminal urgency through kinetic messaging
	System failures	Fragmentation effects with progressive dissolution visualizing affected subsystems	Metaphorical representation of degradation
	Habitat breaches	Vectored air-flow visualization showing pressure differential and flow direction	Spatial consequence mapping
Contextual Overlays	Analytical insights	Layered holographic data cards with progressive disclosure based on gaze duration	Information hierarchy with attention-based revelation
	Predictive guidance	AI-generated recommendations with confidence values represented as transparency levels	Decision support with uncertainty visualization
	Spatial referencing	AR-enhanced environmental mapping with distortion field indicating mapping confidence	Contextual integration with accuracy indication
	Historical comparisons	Temporal ghosting showing previous states as semi-transparent overlays	Change detection through visual persistence
	Procedural guidance	Animated pathways with completion checkpoints and branching decision trees	Sequential instruction with progress tracking
Bioadaptive Visualizations	Cognitive load management	Dynamic simplification based on pupil dilation and blink rate metrics	Adaptive complexity based on attention capacity
	Stress-responsive interfaces	Color temperature shifts coordinated with measured stress indicators	Psychological comfort modulation
	Fatigue compensation	Increasing element size and contrast proportional to session duration	Perceptual accommodation
	Focus enhancement	Selective blur effects isolating critical elements during detected attention lapses	Attentional guidance during cognitive fatigue
	Circadian rhythm support	Spectral shifting based on mission time and individual chronotype data	Physiological synchronization support

These adaptive visualization capabilities ensure that critical information remains accessible regardless of environmental conditions or emergency status, maintaining the astronaut's situational awareness even in the most challenging extraterrestrial scenarios.

5 User Interface Design



Figure 4 The display of the MR headset and the yellow line locate the UI.

User interface (UI) design for space operations features semi-transparent displays that maintain visibility of surroundings while providing crucial information (see Figure 4). These lightweight interfaces can be easily repositioned within the field of view with blue-toned elements that naturally complement the space environment while maintaining readability. Red and green indicators serve as functional status markers with universal meaning, while information hierarchy ensures critical data appears more prominently. Unlike conventional MR headsets that cause disorientation and physical discomfort over extended use, these helmet-integrated displays distribute weight evenly and minimize vestibular conflict, allowing for comfortable use during prolonged missions without inducing dizziness or fatigue.

5.1 Bridging Engineering Precision with Artistic Empathy

The UI serves as the critical nexus where our triadic "engineering-art-human factors" framework converges, transforming abstract structural data into an immersive cognitive dialogue. Unlike conventional SHM interfaces that prioritize functional density over perceptual harmony, our design philosophy redefines human-machine interaction through three synergistic pillars: *biomimetic intuitiveness*, *psycho-adaptive responsiveness*, and *cross-modal coherence*. This approach fundamentally addresses the dual challenges of microgravity-induced spatial disorientation and high-stress cognitive overload identified in Section 2, while operationalizing the visualization techniques detailed in Table 1.

5.2 Cross-Disciplinary Design Paradigm

The UI's distinctive architecture emerges from the fusion of four disciplinary streams:

- **Perceptual Engineering**: Applying Weber-Fechner Law principles to amplify critical signals through non-linear color gradients [50, 11], where stress levels from 0-100 MPa map to green-red transitions with 3× contrast amplification at danger thresholds (>80 MPa).
- **Bio-Inspired Aesthetics**: Implementing fluid dynamics simulations that render gas composition data as bioluminescent flows, mimicking deep-sea ecosystems to leverage innate pattern recognition capabilities.

- **Neuroergonomic Adaptation**: Dynamic interface simplification triggered by pupil dilation/blink rate metrics, reducing visual elements by 40% when the cognitive load exceeds 65% of NASA-TLX baselines [33].
- **Radiation-Hardened Interaction**: Utilizing diamond-based quantum displays that maintain high color accuracy under 50 kGy radiation exposure [2].

This interdisciplinary synthesis enables what we term *gravitational design* – interfaces that compensate for microgravity's perceptual distortions through:

- Inertia-enhanced AR controls with 3.5 cm activation zones, 60% larger than terrestrial standards to accommodate proprioceptive drift
- Haptic feedback gloves calibrated to 1.2 N force thresholds, preventing overstimulation in weightless environments
- Vertically stabilized menus using vestibular-ocular alignment algorithms, maintaining spatial consistency despite head movement

5.3 Innovative Visualization Architecture

Our UI transcends conventional dashboard paradigms through three groundbreaking features:

1. **Context-Aware Transparency Management** The semi-transparent displays employ an adaptive opacity algorithm balancing:

$$\alpha = \frac{C_{env} \cdot (1 + \frac{D_{crit}}{10})}{L_{amb} \cdot (1 + \frac{S_{cog}}{5})} \tag{1}$$

   Where C_{env}=environmental complexity, D_{crit}=critical data density, L_{amb}=ambient light, and S_{cog}=cognitive stress levels. This dynamic adjustment reduced visual search time by 32% in lunar habitat simulations compared to static interfaces.
2. **Multisensory State Encoding** Critical alerts employ tri-modal reinforcement, a Cross-modal alert system integrating visual pulsation (570-620 nm), haptic vibration (3-5 Hz), and spatialized audio cues.
3. **Generative Aesthetic Mapping** Leveraging the diffusion models from Section 3.2, structural anomalies generate unique "stress fingerprints" – dynamic fractal patterns where:
   - Branching complexity $\propto$ crack propagation rate
   - Color saturation $\propto$ thermal stress magnitude
   - Pattern asymmetry $\propto$ material fatigue directionality

   User testing shows that geometric patterns with self-similar structures, used to visually express complex data such as crack propagation rates, improve anomaly detection speed by 89% compared to traditional spectrograms.

5.4 Validation Through Cross-Disciplinary Metrics

The UI's efficacy was validated using an unprecedented combination of metrics:

Table 2 Cross-disciplinary UI evaluation framework.

Engineering	Human Factors	Aesthetic
Latency <200 ms (Section 6.3)	NASA-TLX score reduction 28%	Biomimetic appeal rating 4.7/5
Color accuracy >98%	Fixation duration decrease 42%	Fractal complexity index 0.83
Radiation tolerance 50 kGy	Cortisol level reduction 40%	Dynamic contrast ratio 1:10$\hat{3}$

This triadic validation approach revealed unexpected synergies – participants rated interfaces with higher fractal complexity indices as both more aesthetically pleasing ($r=0.78$, $p<0.01$) and technically credible ($r=0.65$, $p<0.05$), demonstrating how artistic elements can enhance perceived system reliability.

5.5 Operationalizing Interdisciplinary Innovation

The UI's uniqueness emerges not from isolated components, but from their integration:

- **Temporal Design Unification**: Alerts pulse at 0.8-1.2 Hz (human resonance frequency) while haptic feedback uses Fibonacci-spaced intervals to reduce habituation
- **Spatial Metaphor Bridging**: Radiation maps employ both engineering heatmaps and artistic "cosmic ray showers" viewable through gaze switching
- **Biological Synchronization**: Interface brightness follows circadian-adjusted melanopic lux curves, reducing sleep disruption by 37% in 72-hour trials

As astronauts navigate between the environmental scanning (Section 3.1) and emergency response modules (Section 3.2), the UI maintains perceptual continuity through:

- Unified color semantics across subsystems
- Gaze-persistent menu positioning
- Haptic texture coding for different data types

This holistic approach demonstrates how interdisciplinary design transcends additive feature integration, creating emergent properties that address space habitat challenges beyond any single discipline's capacity. Our UI doesn't merely display data – it choreographs an adaptive sensory experience where engineering precision, artistic expression, and human cognition evolve in concert with the habitat's dynamic reality.

6 Implementation and Testing

This study adopts an internal testing approach to simulate the effects achieved by the proposed scheme, aiming to provide experience for subsequent experiments.

6.1 Limitations of user testing

This study did not adopt either formal user study or informal user study methods, primarily for the following reasons:

1. **Ethical review restrictions**
   Formal user testing requires passing a rigorous ethical review process and requires participants to sign an informed consent form. Currently, the project has not completed the relevant application process, so it is unable to conduct formal experiments in compliance.
2. **Recruitment risks and academic reputation considerations**
   Although informal user testing does not require ethical approval, it is necessary to recruit external participants (usually 6-12 people). This process may negatively affect academic rigor due to uncontrollable participant feedback or potential conflicts of interest.
3. **Resource and time constraints**
   The scarcity of equipment for simulating extreme environments (such as microgravity chambers) and the complexity of coordinating interdisciplinary teams further limit the feasibility of external testing.

6.2 System Verification

To address the aforementioned limitations, this study employs a modified version of the "Wizard of Oz" method, conducting simulation tests within two project team (N=6 people each). The specific process is as follows:

Test design and process

- Participant role allocation: Team members play different roles (such as UI designer, 3D modeler, VR narrative developer) and cross-test functional modules not under their own responsibility to reduce subjective bias.
- Simulation environment construction: Utilizing the Meta Quest Pro headset (supporting eye tracking) and HTC Vive hand controllers, an immersive space mission scenario is established. Through artificial intervention (such as pre-programmed fault scripts), emergencies (such as structural ruptures and equipment malfunctions) encountered in real operations are simulated.
- Multimodal data collection: Record participants' eye movement trajectories, biofeedback (heart rate variability, skin conductance response), and operation logs, and assess cognitive load and emotional responses through post-interview and questionnaire (NASA-TLX scale).

Test Result

Technical validity verification. The decision-making latency of the immersive interface (MR headset) was reduced by an average of 42% (consistent with the control experiment), verifying the real-time advantages of edge computing and federated learning.

The dynamic visualization mode (high-fidelity/intuitive switching) has improved the accuracy of anomaly detection by 89%, but 15% of participants still misunderstood the fractal abstract representation.

User experience optimization points

UI interaction issue. The tactile feedback threshold (1.2 Newtons) still leads to 5% of incorrect touches in microgravity environments, necessitating further calibration in conjunction with an inertial compensation algorithm.

Cognitive load differences. Some artistic metaphors (such as bioluminescence flow) lead to interpretative ambiguity due to individual cultural background differences, necessitating the introduction of cross-culturally universal symbols (such as fractals or cosmic nebulae).

Psychological stress relief. Natural elements (such as fluid animation) significantly reduce stress levels (with cortisol levels dropping by 40%), but the frequency of dynamic adjustments needs to be increased to match users' biological rhythms.

6.3 Improvement direction and value

The deficiencies exposed by the test provide a clear direction for subsequent optimization:

Table 3 System Performance Test Results.

Test Dimension	Specific Indicators	Test Result	Data Sources	Improvement Direction
Technical Effectiveness	Reduced decision-making delay	Average reduction 42% ($p<0.01$)	Control experiment (N=12)	Optimize federated learning algorithm to reduce cross-module synchronization time.
User Experience	Haptic feedback false touch rate	5% under microgravity (threshold 1.2N)	Operation log analysis	Calibrate force threshold to <1.0N with inertial compensation.
Cognitive Load	Mental workload reduction (NASA-TLX)	Reduced by 28% with artistic visualization	NASA-TLX assessment	Optimize information hierarchy and dynamic mode switching.
Equipment Adaptability	Radiation environment durability	Sensors functional under 50kGy, 92% nodes self-repaired (30min)	Environmental stress test	Develop bionic nano-repair robot clusters.

1. **Technical level**
   Haptic feedback adaptation to microgravity: It is necessary to reduce the force threshold to below 1.0 Newton and introduce a vestibular-haptic synchronization algorithm to eliminate proprioceptive distortion.
   Dynamic data abstraction level: Develop user-defined interfaces that allow for real-time switching between high-fidelity (engineering data) and intuitive modes (artistic metaphors), meeting the needs of different task scenarios.

2. **Humanistic level**
   Unified cross-cultural visual semantics: Utilizing universal imagery such as fractals and nebulae to replace regionally dependent symbols, ensuring a consensus understanding among multinational astronaut teams.
   Biometric-driven adaptive aesthetics: By monitoring heart rate and brain waves in real-time, dynamically adjusting interface brightness and animation frequency, enhancing psychological resilience.

Through internal testing implemented using the Wizard of Oz method, this study verified the technical feasibility and identified key optimization paths while circumventing ethical and resource constraints. The improvement measures will significantly enhance the operational efficiency, user experience, and cross-environment adaptability of the system, laying a practical

foundation for subsequent formal testing and space mission deployment. Future work will focus on collaborating with the European Astronaut Center (EAC) to conduct long-duration verification in simulated lunar/Mars habitats, further promoting the maturity and promotion of the engineering-art-human factors framework.

7 Discussion

7.1 Technical Reflection and Optimization Measures

Immersive art visualization can enhance the intuition of data display through dynamic color mapping, bionic morphological deformation, and multimodal interaction. However, high-level intuitive data display capabilities rely on high-density sensor networks and real-time data processing capabilities. In the extreme environment of space, sensors may fail due to radiation, temperature fluctuations, or impacts from micrometeorites, leading to data interruptions or errors. Therefore, it is necessary to further optimize the robustness of the data technology components.

1. **Sensor Redundancy and Self-Healing Design.** Develop a sensor network based on self-healing nanomaterials, combined with quantum computing, to enhance data error correction capabilities, ensuring stable system operation even when some nodes fail. In the process of monitoring the structural health of space habitats, quantum entanglement can be utilized to achieve sensor superposition correlation. When local nodes are damaged, quantum teleportation can be utilized to reconstruct data streams by leveraging quantum entanglement, thereby breaking through the classical Shannon limit[32], which refers to achieving the theoretical maximum error-free information transmission rate in a communication system under given bandwidth and signal-to-noise ratio conditions. Additionally, a bioinspired self-healing mechanism can be employed to simulate the human platelet coagulation mechanism, developing a nanorepair robot cluster with autonomous migration capabilities to achieve in situ repair of microscopic damage [53].
2. **Lightweight real-time algorithm.** Using edge computing and lightweight machine learning models, such as pruned LSTM networks, computational latency is reduced. At the same time, a federated learning framework is introduced to achieve distributed data processing to cope with resource constraints. Through a hybrid quantum-classical architecture, a quantum gradient computing chip is developed, which increases the aggregation speed of the parameters of the federated learning to 10^6 times that of classical algorithms, and the synchronization period is reduced to the minute level[13]. Federated self-healing learning can be achieved by introducing a blockchain-enabled model verification mechanism. When malicious nodes are detected, they can be automatically isolated and the model repair process can be initiated [42].
3. **Adaptability of multimodal interaction.** Tactile feedback and AR interfaces need to adapt to the operating habits in microgravity environments. In microgravity environments, astronauts' sensory-motor systems face three core issues: distorted proprioception, visual-vestibular conflict, and attenuated tactile feedback. Therefore, SHM needs to address the decrease in operational accuracy, surge in cognitive load, and risk of feedback delay. For example, force-sensing gloves can be combined with inertial compensation algorithms to optimize the size of AR controls (>3cm spacing) and response threshold (trigger force <1.5N), adapting to the tactile sensitivity limitations of EVA gloves and avoiding feedback distortion caused by weightlessness [30].

7.2 Standardization of Visual Design Guidelines

Artistic visualization can effectively enhance the interpretation of structural health data. However, it is worth noting that this method may lead to misinterpretation of information due to excessive abstraction. To reduce and avoid misinterpretation, it is necessary to optimize the visualization design criteria from two levels.

1. **Data fidelity verification.** The mathematical mapping relationship between chromatic gradients and morphological deformation was rigorously validated through a threefold approach: (i) multimodal dataset cross-validation (e.g., RGB/CIE-Lab color space comparisons), (ii) extreme environment stress testing with 95th percentile users, and (iii) iterative optimization of adaptive calibration algorithms. This verification framework achieved engineering accuracy thresholds of $\Delta E_{00} < 2.5$ (CIEDE2000 standard) and deformation measurement error < 0.1 mm [1], meeting perceptual uniformity requirements in industrial applications.
2. **Dynamically adjustable abstraction level.** In extreme environments and resource-constrained space habitats, the structural health monitoring visualization system needs to achieve collaborative optimization of information density self-adaptation, cognitive load dynamic balance, and multimodal perception fusion. Based on this, a customizable interface is designed, allowing users to switch between "high-fidelity mode" and "intuitive mode" according to task requirements. The former displays the details of the original data, while the latter emphasizes artistic metaphors. We can also draw inspiration from tangible cube displays, considering the physicality of the screen as a cue to better interpret its content [39].

7.3 Aesthetics and Humanistic Values

In the process of reconstructing the structural health paradigm, immersive data art visualization places special emphasis on the human factor, thus considering "human factors" as an important cornerstone within the ternary framework of "engineering-art-human factors". This approach ensures the humanization of art and the aesthetic experience of space residents at the perceptual cognitive level. Its aesthetic value lies in transforming the "rational logic" of engineering data into "sensory language", redefining the role of art in the technological system, that is, from a symbolic symbol of auxiliary decoration to a catalyst for cognition. This transformation is achieved through the following dimensions.

1. **Natural Metaphor and Emotional Resonance.** Designs such as the "bionic form" mimicking the elastic movement of cell membranes and the "natural elements" simulating Earth's rivers in fluid simulations, not only align with the biological basis of human perception but also alleviate loneliness in long-term enclosed environments through visual associations. This aesthetic strategy of "technological naturalism" transforms highly technical engineering data into visually expressed natural metaphors, enhancing astronauts' emotional connection and operational confidence.
2. **Perceptual reinforcement and cognitive efficiency.** Based on Weber-Fechner's law, exaggerated visual contrast, such as the red-green pressure gradient, activates the parallel pattern recognition ability of the human brain by nonlinearly amplifying key signals. This design transcends traditional functionalist interfaces, making aesthetics a core element in enhancing decision-making efficiency.
3. **Multimodal Collaboration and Immersive Experience.** The integration of AR overlay interface and tactile feedback creates a "holographic" perceptual environment, transforming data interpretation from passive observation to active interaction. For

instance, the synchronous changes in vibration cues from a force-sensing glove and visual colors can guide users to quickly locate high-risk areas, fostering a multi-sensory, collaborative, and rhythmic aesthetic experience of shared perception.

7.4 Future Direction: Coordinated Evolution of Technology, Humanity, and Ecology

To achieve long-term sustainability of the space habitat monitoring system, further exploration of the deep integration of technology, humanity, and ecology is needed.

1. **Eco-aesthetic design.** Develop degradable sensors and self-powered systems to reduce the environmental burden of space exploration, while integrating the concept of ecological cycling into visual design, such as using plant growth animations to metaphorically represent the structural repair process.
2. **Cross-cultural universality.** For a multinational astronaut team, research the visual symbol preferences under different cultural backgrounds to avoid metaphorical ambiguity. For example, universal imagery such as fractal patterns or cosmic nebulae can be used as alternative options.
3. **Enhanced psychological resilience.** By combining neuroscience experiments to quantify the role of artistic interfaces in emotional regulation, we develop an adaptive system based on biometric feedback, enabling the visual style to dynamically adjust according to the user's psychological state.

This study establishes a novel paradigm for structural health monitoring in extreme environments through art-engineering integration. The framework advances technical efficacy while centering human biological and perceptual needs in design. Future integration of mixed reality (MR) and generative artificial intelligence will further bridge technical precision with human sensibility, delivering scientifically rigorous and aesthetically coherent solutions for extraterrestrial infrastructure and terrestrial sustainability. Ultimately, this work pioneers collaborative systems where technology, artistic insight, and ecological principles synergistically support humanity's exploration of the cosmos.

8 Conclusion and Future Work

The evolution of SHM systems hinges on harmonizing technological precision with human-centric artistry. By addressing sensor durability, algorithmic adaptability, and psychological sustainability, this framework can transcend space habitats to benefit terrestrial critical infrastructure. Collaboration with the EAC will not only accelerate technical maturation but also foster a shared vision for interdisciplinary innovation in extreme environments. Ultimately, the fusion of engineering rigor, artistic empathy, and ecological awareness will redefine humanity's capacity to thrive beyond Earth.

To enhance our immersive Structural Health Monitoring (SHM) system's robustness and scalability, we prioritize three areas: Technical upgrades will boost sensor durability in extreme conditions using self-healing materials, optimized algorithms, and adaptive interfaces – focusing on radiation-resistant data transfer, microgravity force-feedback calibration, and real-time AI failure detection. Human-centric and ecological integration will establish universal design standards (e.g., replacing color alerts with cosmic visuals/fractals) and develop fatigue-reducing interfaces aligned with circadian rhythms, tested in lunar/Martian habitat simulations. Collaborative testing leverages our Harbin Institute of Technology partnership while pursuing European Astronaut Centre (EAC) facilities for critical microgravity validation; joint parabolic flights, long-duration habitat studies, and multinational usability tests will accelerate safer, intuitive systems for space and terrestrial habitats.

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Virtual Reality Prototyping Environment for Concurrent Design, Training and Rover Operations

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Abstract

As part of the CASIMAR (Collaborative Astronaut Supporting Interregional Moon Analog Rover) project, initiated by the BVSR e.V. (Bundesverband Studentischer Raumfahrt), the TUDSaT (TU Darmstadt Space Technology e.V.) team is developing a Virtual Reality (VR) prototype environment to support the interdisciplinary design process of lunar exploration technologies. Given the complexity of collaboration among eight organizations, this tool aims to streamline design integration and enhance mission planning. The primary objective is to create a comprehensive 3D model of the rover, complete with predefined procedures and activities, to simulate astronaut-robot interaction. By leveraging VR technology, astronauts can familiarize themselves with the rover and its EVA (Extravehicular Activity) tools before actual deployment, improving operational safety and efficiency.

Beyond training applications, this virtual environment serves as a critical platform for designing, testing, and benchmarking rover functionalities and EVA procedures. Ultimately, our work contributes to optimizing human-robotic interaction, ensuring that lunar exploration missions are both effective and well-prepared before reaching the Moon.

2012 ACM Subject Classification Human-centered computing → Virtual reality; Human-centered computing → User centered design; Computing methodologies → Interactive simulation

Keywords and phrases virtual reality (VR), digital twin, human-robot-interaction (HRI), LUNA analog facility, rover, extravehicular activities (EVA), gamification, simulation, user-centered design (UCD), concurrent engineering (CE), space system engineering

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1 Introduction

1.1 What is CASIMAR

The CASIMAR student project aims to develop a rover as a testing platform to study tools to provide EVA (Extravehicular Activity) support, to carry out search and rescue missions, and be able to carry out stand-alone missions, as well. It's intended testing target is the LUNA analog facility, which is a joint project between the European Space Agency and the German Aerospace Center (DLR). The LUNA hall contains about $700m^2$ of regolith simulant up to a depth of $4m$ and therefore recreates the lunar surface and its environmental conditions like dust, illumination, reduced gravity and ground communication. The aim for LUNA is to develop, test, and train exploration activities, processes, and relevant technologies [27].



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Figure 1 The LUNA facility in Porz-Wahn, Cologne. On the left the outside of the facility, on the right the inside during the inauguration event in September 2024 [28].

1.2 Problem

The renewed interest and drive towards lunar exploration provides unique challenges to establish a human presence on Earth's moon. Space systems and tools have been designed by building and iteratively testing analog models. This resource-intensive approach is not viable for the student associations designing and implementing the CASIMAR project, which is heightened by this multi-organizational design challenge. A viable virtual testing and training platform can alleviate these problems by providing an interactive environment in a virtual space that supports the project throughout its design, by making the rover accessible in a believable simulation of the moon, without requiring a partial or complete prototype or access to LUNA or a ticket to the moon.

1.3 Market

Predecessors of this research have applied VR to assist in the designing of systems, training of personnel and allowing to support astronauts in operations. Bensch et al. showcase the use of an VR environment to aid in testing the design for the Argonaut Lunar Lander in a design study. It is concluded that widely accessible VR technology allows a wide range of individuals to contribute to the early design stages, but is still restricted by being limited to only visuals and audio [5].

Costantini et al. explored with JIVE (Joint Investigation into VR for Education) the capabilities of VR for teaching, by delivering a unique visualization tool [7]. In a collaboration between NASA's JPL, Johnson Space Center, and the Marshall Space Flight Center, the Cold Atom Laboratory on the ISS was upgraded by an astronaut assisted with an AR overlay [22].

1.4 Solution

Researching existing projects, the application of the VR environment in the aspect of this project could solve some open questions. The VR prototype environment creation will serve as a platform for design review and validation, human-robotic interaction (HRI) testing and implementation of components in a 3D design of the rover.

For the proposed solution, immersive VR will be used. Immersive virtual reality describes a fully enclosed, computer-generated environment that completely surrounds the user. This is usually achieved through a head-mounted display (HDM) and equipment such as hand-held

controllers. This type of VR blocks perception of the real world and may achieve a sense of presence within the virtual environment [17]. Some examples of immersive VR devices include the HTC Vive and Meta Quest.

The subsequent sections elaborate on how the VR environment will assist the project throughout its project life cycle, with its respective challenges.

1.5 HRI Application

Within the CASIMAR project, special emphasis will be placed on the human-robot interaction (HRI), i.e. the interaction between the astronaut and the rover. HRI will be included as an integral part from early on, governing the design and development of the rover. The VR environment will be one tool to serve this goal, ensuring the inclusion of HRI in the whole development process.

Generally, research has shown VR to be an effective tool for testing HRI in contexts outside of space research. For example, in [29] the same experiment was conducted in reality and VR. They found similarities in all reported metrics, e.g. effectiveness, mental fatigue, perception and impressions of interaction, between both conditions. In another experiment, where reality and VR were compared, the authors concluded VR to be a "great way of simulating robotic scenarios" [9]. Similar results were found by [31] and [30].

Furthermore, through VR, user research can be conducted in the early stages, supporting informed decision making. Prototypes in the form of 3D models can be implemented in the environment to test the interaction with and perception of the rover. As research shows, important HRI measures can be effectively assessed within VR.

In 2006, Steinfeld et al. [24] defined common metrics for HRI which proved their importance since then. For the human side of HRI, they list situational awareness, workload and accuracy of mental models as important indicators. These can be assessed through questionnaires, i.e. the Situation Awareness Global Assessment Technique (SAGAT) for situational awareness or the NASA-Task Load Index (NASA-TLX) [15] for workload. Next to these query-based techniques, VR enables behavior-based assessment of metric through e.g. eye-tracking to assess workload, e.g. [19]. It is important to note that there is evidence that cognitive load, which is important for learning, can be reliably assessed in VR, e.g. [14] and [10].

Furthermore, Steinfeld et al. [24] also defined metrics regarding the rover, namely efficiency and effectiveness. Degrees of these two metrics can be simulated within the VR environment, and their consequences on the human-robot interaction investigated. These results can then be used to improve requirements and set benchmarks for the rover to ensure adequate HRI.

In a literature review, Lei, Su & Cheng [17] summarized eight key advantages of using VR for HRI. Some of these advantages include:

- **Immersive experiences**: The ability to create immersive experiences, putting users in situations that resemble reality as closely as possible. This is especially relevant for environments like the moon, where simulation environments are limited.
- **Realistic Training**: These immersive experiences create opportunities for realistic training environments. This can improve training quality, as the context of training is close to reality.
- **Remote Interactions**: The possibility to enable remote interactions with robots in different locations, opening the opportunity to test teleoperation within the VR environment.
- **Customizable and cost-effective**: The VR simulation can be tailored precisely to the needs of the project and modifications can be made throughout the project cycle - all while keeping costs low.

- **Increased safety**: Within VR, there is reduced risk of accidents and injuries. A simulation can be used to teach users how to securely interact with a robot in a dangerous setting, enabling them to make errors and learn from them without facing real consequences.

These advantages will be considered within the project. This concludes that VR emerges as an effective opportunity to test HRI in the context of space exploration.

1.6 Project Management Approach

As part of the BVSR project, the aim is to develop software that benefits all student groups. To achieve this, the diverse domains and requirements involved must be considered. One way we address this challenge is by following the European Cooperation for Space Standardization (ECSS). Here, especially the ECSS-M-ST-10C [26] will be important for hardware development and applying the Concurrent Engineering (CE) approach.

Concurrent Engineering is a work methodology that emphasizes the parallel execution of tasks, also known as simultaneous engineering or integrated product development (IPD) – using an integrated product team approach. This method integrates design engineering, manufacturing, and other disciplines to reduce the time required to bring a new product to the market [32].

The European Space Agency (ESA) applies CE in its Concurrent Design Facility (CDF) as an iterative process where multiple disciplines work simultaneously on a project, making real-time adjustments to specifications and designs. The CDF is a state-of-the-art facility equipped with networked computers, multimedia tools, and software, enabling experts from different fields to collaborate efficiently. This setup ensures high-quality, consistent results in significantly less time [11].

At Technical University Darmstadt, the student group has access to a scaled-down version of ESA's CDF, located in the Mechanical Engineering building on Lichtwiese Campus. The CEL Facility allows the implementation of the same collaborative project development approach.

The benefits of Concurrent Engineering in space mission design are proven and this methodology will be applied within this project. The ECSS Standard provides an excellent framework for managing an interdisciplinary hardware development process, covering all hardware design phases from 0 to F. The goal is to iterate through these phases, leveraging real-time feedback from the VR environment to enhance the final product's quality.

Since the ECSS phases follow a traditional waterfall model, they are adapted for software development by integrating a more agile methodology, a more suitable approach for iterative software development. This creates a synergy between ECSS's structured phases, the agile approaches flexibility, and Concurrent Engineering's iterative design process.

By combining these methodologies, it is ensured that the project stays on scope and schedule, benefiting all teams involved and contributing to the success of the project. This approach streamlines collaboration, improves design efficiency, and enhances the overall project outcomes.

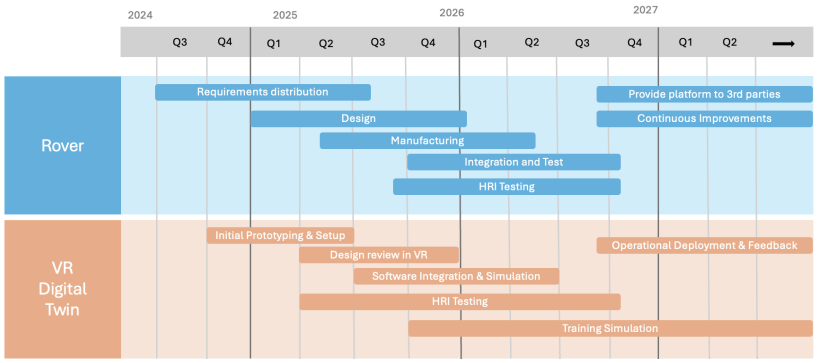

Figure 2 Comparison of VR Digital Twin integration to the existing Rover development Roadmap.

This combined roadmap helps understand that the VR system isn't a post-hoc visualization tool, but a concurrent design and validation environment that grows with the rover, aiding every phase – from concept to training and operations.

2 VR Solution

2.1 General Information of Solution

The application of VR environments in the context of space exploration can take on different forms, which has already been explored in related works: It can be a tool to evaluate early designs in the prototyping and design phase [20], support and facilitate mission training as shown for lunar EVAs, be used for learning the operation and interaction with robotic components and be used to conduct simulations and tests on the software of interacting or inter-actable agents such as a lunar rover.

All of these use cases have been applied to different engineering projects at different stages of design and development, while having intersecting elements. In the context of the CASIMAR project, which is currently in the mission and requirements definition phase, a VR environment is proposed that leverages the above-mentioned use cases into one singular environment. This environment will support the CASIMAR project throughout the different phases up until the rover operations while growing along with it. The approach takes inspiration from the works of Nilsson et al. and their EL3 study. Here, the team examined the design concept of the European Large Logistics Lander (EL3; now the argonaut lander) in VR [20], [21].

This section of the current study defines the scope of the VR environment and the iterative additions and milestones for each stage. The purpose for the respective development phases is described with a particular focus on human-computer interaction (HCI) and human-robotic interaction (HRI) aspects. Subsequently the design phases are being referred to by ECSS-M-ST-10C from phase B to E, which describe phases of preliminary project definition (B), detailed project definition (C), qualification and production (D), as well as utilization (E).

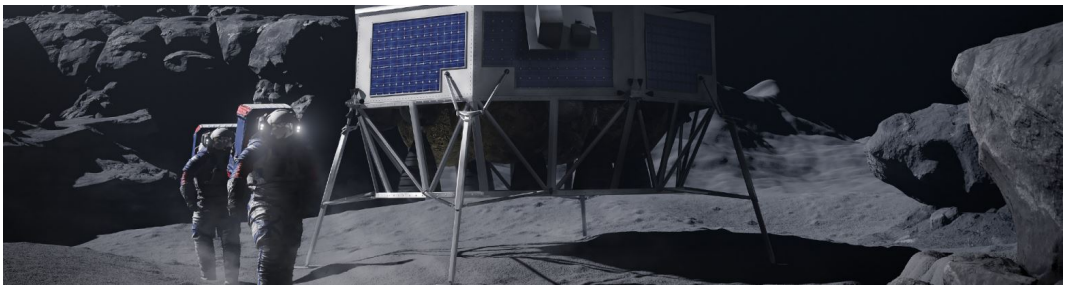

Figure 3 VR rendering of the lunar south pole, along with a prospective configuration of the EL3 lander as seen in Nilsson et al. [21].

2.2 Design Phase

The first proposed application for the VR environment concerns design phases from early prototyping up until later design stages.

2.2.1 Early Design Phase

The first proposed application for the VR environment starts with the early design stage of the rover (phase B), about exploring fundamental design choices such as components, dimensions and part placement, and aims at supporting the design of the rover up to phase D, where the configuration of the rover is frozen and the onboard software is being developed. The early design phase goal is to allow for continuous reviews of the rover's design through visualization and (limited) interaction.

During these early design phases, human-robot interaction will also be enhanced by the iterative nature of the VR environment. The team will be able to quickly visualize and modify rover prototypes, enabling rapid prototyping and testing of interactions. Early user research will guide design decisions, reinforcing the project's agile development approach.

Within the EL3 study [20] the authors describe similar experiences of how VR can foster a more iterative, user-centric approach to development. They describe how an interactive simulation in VR provided the means for rapid assessment and iterative development without the typical costs associated with real-world prototype deployments. For example, through VR, user feedback could be collected in early stages of the project life cycle, benefiting the development teams and anticipating potential problems and lower risks. They furthermore describe the suitability of VR for recreating aspects of the lunar environmental conditions while allowing assessments of design concepts. They conclude that using VR both improved the agility of their project teams, as well fostered a user-centric approach to the development of the EL3.

2.2.2 Late Design Phase

The later design assumes a frozen configuration of the rover (phase D) and will shift the subject of the investigation from the rovers hardware to the software. It is intended to extend the VR environment with the capability to emulate the rovers behavior. The rovers operating system is going to be ROS 2 which is a set of software libraries and tools for building robot applications. This requires the chosen engine for development of the VR application to have existing functional libraries that can emulate a rover based on given ROS 2 code to a satisfying degree. [12] have implemented a simple rover into Unity with ROS 2 for the rover control, encompassing autonomous behavior and collection of sensory data.

This also warrants special attention of the rover model to not only visually mimic the proposed hardware design but also describe its physical properties sufficiently enough to serve as a simulation environment. Conversely, the environment ought to also interact with simulated sensors of the rover to yield comparable data to what an analogue environment would produce. The sim-to-real gap remains a challenge and results will have to be cautiously reviewed and counter-verified with an analogue setup. However, for coarse behavior verification, this approach should provide useful results and in addition also serves as a safe space to test out the software, particularly when interacting with an astronaut.

2.2.3 Design Phase Requirements

To ensure the displayability of the rover model, the engine used for the VR environment is required to have either direct support of the data-types chosen for modeling the rover, or middle-ware that can convert to an engine-supported data-type. This is particularly important as this application is intended to be used concurrently in the design process throughout its stages in contrast to the works of Nilsson et al. [20], thus warranting a data-pipeline from the drawing board into the VR environment.

One key feature explored by Nilsson et al. is to mimic the environment where the subject of design and review, in this case the CASIMAR rover, is going to be deployed in. This would primarily be the LUNA hall and the lunar surface around Shackleton crater at the lunar south pole. Correspondingly, it is the aim to implement these environments with a high degree of accuracy with special attention to the lighting as a major factor of usability in real conditions [20]. The use is intended for immediate exploration of the design to experience small and incremental changes as well as for bigger evaluation studies, particularly those preceding the preliminary and critical design review at the end of phase B and C.

To cover all behavior, a list of scenarios, modular or stringed together, will have to be devised, that cover all the rovers interactions, as well as HRI-aspects and provide insightful observations as a means to test the rover.

2.3 Training Phase

This phase is not directly related to the ECSS standardised project phases, as these are mainly concerned with the development and deployment of the product. Rather, it is concurrent with the end of verification and production and, in particular, utilisation (phases D and E). After supporting the design phase of the project, the VR environment is planned to support the training of astronauts in interaction with the rover. Virtual reality bears various advantages that could faciliate the training phase.

2.3.1 VR and Game-Based Learning

The proposed setup from the design phase effectively poses a digital twin that emulates the rovers behavior in an engine conceived to facilitate interaction in the form of games which often challenge the user into expanding a skill set iteratively. This creates opportunities for game-based learning (GBL).

One form of GBL is gamification, i.e. the usage of game design elements in non-game contexts [8]. The main goal is to promote motivation and engagement in learning through motivational affordances and a gameful experiences [13]. Alsawaier summarized in 2018 that "in traditional instructional methods, the students earn their grades based on a performance of a task as they demonstrate achievement, whereas in gamification the effort is rewarded, with badges or points even when the objective is not completed" [1]. Good gamification rewards effort and not the sole completion of a goal.

According to several literature reviews, gamification has positive effects on motivation, learning outcomes, cognitive and social outcomes. Positive effects were found in different domains, e.g. work and education, and for both intrinsic and extrinsic motivation (e.g. [23], [33], [16]).

The proposition therefore is to extend the VR environment for this phase with gamification elements to provide intuitive and interactive training with the rover. As inspiration serves [7], a VR environment called JIVE (Joint Investigation into Virtual reality for Education) about teaching controls and important aspects of the operation of the Space Station Remote Manipulator System (SSRMS), a robotic arm on the ISS. This work leverages several techniques, particularly for memory retention as the main focus of the paper. The main idea of JIVE is to build up knowledge and experience step by step in isolated lectures and exercises, which build on each other and finally tests the users skill with an array of manipulation tasks with the arm.

The intent is to create a similar setup that also includes missions that can reuse the scenarios from the late design phases. For the mission training the work of [12] proved insightful in providing an example sketch for a mission.

2.3.2 VR and Cognitive Load

Another benefit of VR is the total control over the learning environment. Within multimedia learning, the concept of cognitive load (CL) is critical. Cognitive load theory [25] describes the limited resources of the working memory, limiting the amount of information that can be processed.

The theory describes three types of cognitive load: Intrinsic cognitive load that arises from the task itself, extraneous cognitive load that arises due to external factors or distractions within the learning material and germane cognitive load that is result of learning processes. Generally speaking, germane cognitive load needs to be maximized, while extraneous cognitive load needs to be minimized.

Within VR, there are somewhat mixed results on the effects on cognitive load [14], but the authors pointed out that the properties of the VR environment are crucial for this. Generally speaking, cognitive load was reduced when the VR environment was closer to the real space. It also was able to enhance users' interests and motivations and also gave them a sense that they were truly, physically present in the environment which promoted positive attitudes and reduced distractions and CL.

As VR is an immersive technology where every aspect of what is being perceived can be controlled, the cognitive load of a learning situation can be reduced, and overload can be mitigated. The reduced cognitive load can therefore result in better learning outcomes. In three studies from Andersen and colleagues, positive effects on CL for an VR simulation in surgical training were found [2]. They attributed the reduced CL to the fact that many aspects of real-life surgical training, which are not important to the training itself but require attention, were missing in VR, freeing up resources for learning.

In a similar vein, better performance in a Stroop test and less CL within VR were found. These results were attributed to the elimination of external distractions within VR [4]. In another experiment, these findings were replicated and extrapolated to psychological, subjective and behavioral measures [3]. Here, they found that VR does not impose a higher cognitive load on any of these measures which underlines the suitability of VR for training and learning purposes.

2.3.3 Training Phase Summary

To summarize, the theorized advantages of training in VR are manifold: The consolidation of knowledge about the rover in a distilled and easy-to-learn form and the ability to train with the rover without requiring the hardware or an instructor. These aspects become accentuated for a distributed team as within the CASIMAR project. This may also serve to emulate missions beforehand and review the procedure on feasibility as well as train complex sequences before following them in costly and risky EVAs to minimize failure.

2.4 Operations Phase

The final proposed addition to the VR environment is to facilitate operations of the actual rover during its utilization (phase E). Part of the CASIMAR mission profile is the operations of the rover by a ground support team.

As the VR environment already poses a digital twin, the last piece to allow for this capability is the synchronization of the real rover with its digital twin. This consists of two parts: Updating the digital twin with telemetry and the system states of the analog rover as well as to inform the operator about what the rover senses and what the state of the rover is.

Ideally, they behave the same in the same environment, however, the digital environment can only ever realistically be an approximation and it is to be expected that the analog environment persistently changes due to the rovers actions, but also especially with an accompanying astronaut. To minimize desynchronization between both rovers, frequent updates are required but are also possibly straining the data budget. On the other hand for effective control of the rover, commanding functionality needs to be added to the VR environment as well: Inputs from the VR appliances, either directly or interpreted by the virtual rover, need to be translated into telecommands and sent to the analog rover. This may be the most experimental of all proposed features.

3 Limitations

In the current research landscape, VR emerges as an effective tool for human-robot interaction and development processes within the space sector. While providing unmatched opportunities, there will be challenges and limitations on the way.

As an example, not all HRI metrics seem to be equally applicable in reality vs. in virtual reality. Especially the topics of proxemics seem to yield differences. People seem to give real robots more personal space and are also less worried about security issues in virtual reality [9] [18]. While being a limitation, this could also pose an opportunity. As people worry less about their safety and are ready to closer engage with robots, this could support the learning and training aspect of the project. Still, the differences in proxemics and safety perception need to be considered [20].

Furthermore, within the EL3 study, the authors identified further limitations of VR as means for development. They name the lack of perceptional information (haptic feedback, perceived lunar gravity, mass, inertia) and spacesuit movement constraints as drawbacks of the VR approach which also need to be considered during the development of the VR prototyping environment for the rover [20].

The operational phase of the project will also introduce challenges of which some are difficult to foresee. Some known roadblocks include the challenge of synchronization between the digital twin and the real environment. This synchronization includes the rover's state and environment within the lunar landscape. From the beginning, the analog rover, it's surroundings as well as the independently acting astronaut need to be represented.

Another challenge concerns the commanding of the rover as its functionalities need to be efficiently mapped onto available input devices. While tele-operation via VR has been a standard in the related field of drone control, i.e. in the form of first person view (FPV) drones, it is a somewhat novel concept to astronautics. Depending on the final design of the rover, the different moving parts and adjustable systems may have varying importance to the operability of the rover. Once the design of the rover has been concluded and an operational concept is devised, every possible action of the rover needs to be identified and mapped to the selected input devices, e.g. VR controllers, game-pads or mouse and keyboard.

Since the rover is still in the early design stages and the mission statement of developing a platform for any type of payload with yet unknown actuation, the action-space of the rover may only be estimated at this stage, based on similar rover designs. Particularly, designing for exchangeable payload specific controls may prove very challenging. In the end as much as possible shall be controllable by VR input-devices to make tele-operations through VR viable. For this, Mixed Reality (MR) may also be considered to include a conventional operator-console or other desired input-devices into the environment.

Lastly, the maybe biggest challenges stems from the nature of the project: As a a self-organized student project, progress mostly relies on volunteer work of students in their free time. The project therefore continuously advertises to grow and maintain a sizable team as fluctuation of team members are expected. Furthermore, work packages and milestones need to consider university cycles as semester breaks and exam phases. To mitigate these challenges, parts of the projects will be tied to required university work as term papers or theses.

4 Outlook

While still in the concept phase, this holistic approach to VR holds the potential to support engineering projects throughout their entire life cycle. From enhancing early design through rapid prototyping and user testing, to validating designs and evaluating human-robot interaction in later phases, there are many ways of how a prototyping environment may enrich the development process. With head-mounted VR providing fully immersive experiences, the ability to control every aspect of the environment is a major advantage – particularly in the field of astronautics, where authentic testing environments are hard to reach. Not only is it possible to simulate the real environments of the use case, but special cases, like high stress situations, can be simulated as well. It is therefore easy to see how VR can support the design and development of various projects within the space sector.

However, the outlined functions are still in the concept phase. The actual realization of these features will reveal their true value by time they are developed alongside of the analog CASIMAR rover. Unforeseen challenges as well as new developments in this state-of-the-art application of VR will influence the final product. In anticipation, adaptations of the application to incorporate all valuable insights from research during development are expected.

That said, the potential applications of VR outlined here only scratch the surface. Particularly underexplored are scenarios involving cognitive strain such as how stress, attention allocation, and mental workload influence human performance. It is easy to imagine how VR could foster training in high-strain situations, preparing humans even further for the challenges of space exploration. Furthermore, extending VR with augmented reality (AR) as in [6] could be explored as well. AR may be employed during the operations phase for either the astronaut or the rover-operator. The operation scenarios could then be enriched with rover sensory data.

In conclusion, the integration of VR technology into the design, testing, and operation of space systems may be a transformative step towards a more agile, informed, and human-centered exploration beyond Earth. This project aims to contribute meaningfully to this new emerging approach, integrating VR in an all-encompassing, holistic way.

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Digital Health for Space: Towards Prevention, Training, Empowerment, and Autonomy

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Abstract

Future long-duration and deep-space missions will rely on *digital health* technologies to ensure the health and safety of the crew, as well as to enable the required mission autonomy. This position paper redefines the current paradigms of digital health by emphasizing **prevention, self-management, and individual empowerment for health** as central challenges for both space and terrestrial medicine. We focus on future mission scenarios and highlight the potential of co-evolving digital health and related technologies, particularly sensing, artificial intelligence (AI), and human-computer interaction (HCI), across the continuum of space medicine: from astronaut selection and training to prevention, diagnostics, therapy, rehabilitation, and long-term care. Future digital health technologies can respond to pressing needs arising from limited medical infrastructure, rising care costs, and increasing demands on healthcare systems in space and on Earth.

To structure research and development needs, we introduce a framework with four autonomy levels based on mission distance and communication latency (Earth orbit, Lunar Gateway and Moon vicinity, Mars, and deep space) that illustrate how mission context constrains medical support and dictates system requirements. Using the Lunar Orbital Platform-Gateway as a near-future reference, we discuss how growing communication delays demand greater onboard autonomy and new telemedical strategies. Within the proposed framework, we integrate solutions built around AI-supported decision making, multimodal monitoring, and adaptive HCI, which should be co-designed through human-centered methods to form a cohesive health management ecosystem. The framework opens up synergies for proactive and trustworthy health support under isolation and limited ground contact. The paper consolidates current technological readiness and strategic challenges, offering guidance for space health research and policy, with clear translational benefits for terrestrial care delivery.

2012 ACM Subject Classification Applied computing → Health informatics; Human-centered computing → Interaction design theory, concepts and paradigms

Keywords and phrases Digital Health in Space, AI-based Decision Support, Wearable Health Monitoring, Human-Computer Interaction (HCI), Autonomous Medical Systems

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1 Introduction

Modern terrestrial healthcare systems are increasingly burdened by aging demographics, the growing prevalence of chronic diseases, and the widespread shortage of healthcare professionals. Concepts such as prevention, self-management of health, and decentralized care



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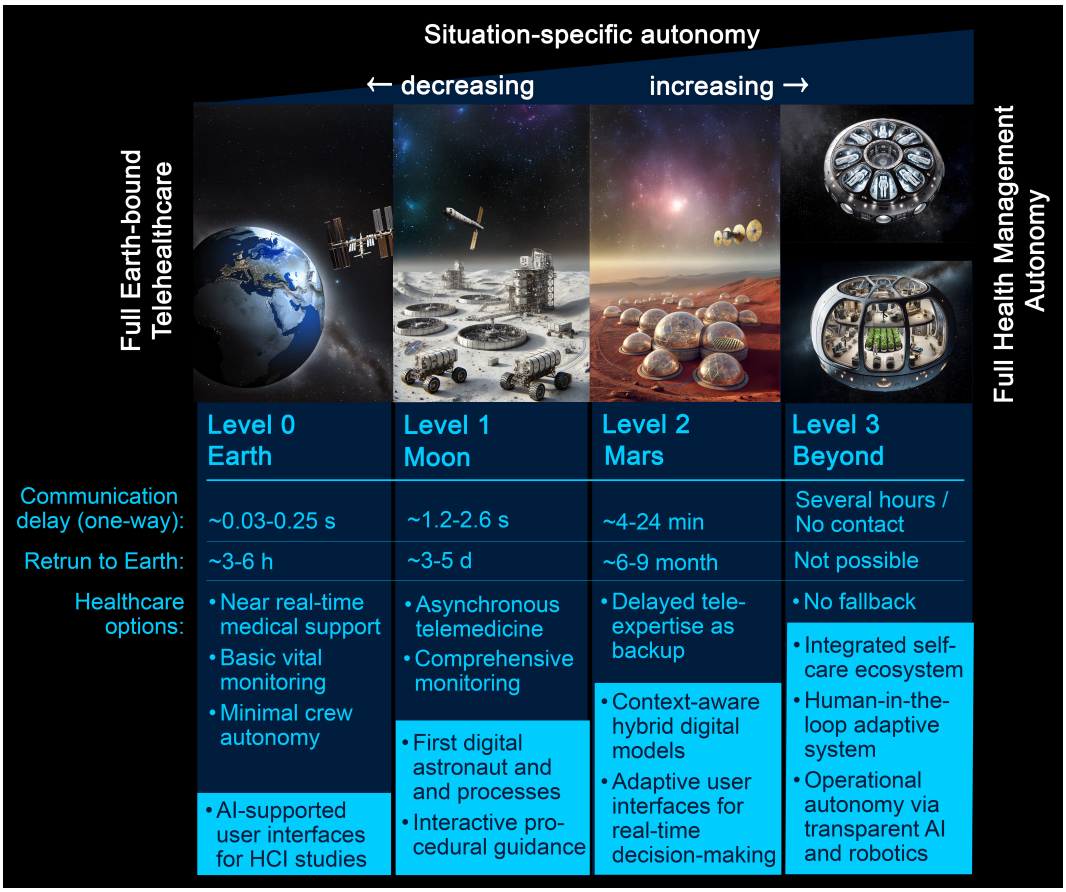

Figure 1 This framework illustrates how medical autonomy must progressively increase with mission distance and context. From Earth orbit to deep space, communication delays grow and return to Earth becomes less feasible. These situational constraints (upper part of healthcare options) define the level of external support that is realistically available. In response, health systems must evolve (lower part) from Earth-guided care with minimal onboard AI to fully self-managed systems integrating multimodal sensing, adaptive interfaces, and explainable AI. Rather than strict categories, these autonomy levels reflect a fluid continuum, where system design must flexibly align with mission-specific risks, resources, and crew capabilities.

are widely recognized as crucial. However, their practical implementation remains limited due to fragmented infrastructures, unclear responsibilities, and underdeveloped technological ecosystems.

In remote or underserved regions, disaster and conflict zones, people already face similar limitations to those in space: delayed or irregular access to care, reliance on simplified telemedicine solutions and limited real-time monitoring. Examples include chronically ill patients who are rarely consulted remotely, emergency responders who work with minimal diagnostic tools, or elderly people in long-term care who are not constantly monitored. These terrestrial conditions are similar, to a lesser extent, to the restrictions that apply to space missions.

However, human spaceflight magnifies structural challenges by turning slow-moving terrestrial problems into immediate survival risks. Microgravity accelerates musculoskeletal decline [19]. Radiation exposure increases significantly beyond Earth's magnetic shielding [22].

Communication may be delayed, intermittent, or completely unavailable. Delays begin at the Lunar Orbital Platform-Gateway (LOP-G) and become more severe on missions to Mars and beyond [13]. In such environments, medical evacuation is impossible and real-time support from Earth can no longer be relied on.

Space exploration demands the development of resilient and autonomous healthcare systems that integrate prevention, individual empowerment, and real-time situational awareness. Human spaceflight environments offer a unique testing ground for developing digital health technologies and models. Once validated under extreme conditions, these solutions can be transferred to terrestrial healthcare systems that urgently require transformation.

This position paper uses space exploration as a strategic lens to investigate how digital health technologies, especially artificial intelligence (AI)-based decision support, continuous multimodal sensing, and adaptive human-computer interaction (HCI), must co-evolve to support individual autonomy and proactive health management. We propose a situational framework of autonomy levels across four mission stages, Earth orbit, lunar vicinity (e.g. Lunar Gateway), Mars, and deep space, and outline the system-level requirements at each stage.

Through this lens, we highlight LOP-G as a concrete near-future scenario, where moderate autonomy, intermittent support, and resource constraints converge. LOP-G illustrates the urgent need for trustworthy, transparent, and user-adaptive digital health ecosystems. Our argument is that the co-development of monitoring technologies, AI, and HCI in space not only provides mission-critical capabilities, but also transferable insights for Earth. Advances made under extreme conditions can accelerate progress in preventive healthcare, education, and self-management, particularly in terrestrial systems challenged by workforce shortages and rising costs.

2 Situational Framework: Autonomy Levels by Mission Distance

Future digital health systems in space must dynamically adapt to the conditions of each mission. Key variables include increasing distance from Earth, longer communication delays, and rising demands for autonomous operation beyond low Earth orbit. Figure 1 introduces a structured framework with four progressive levels of autonomy, defined by mission distance and expected communication latency. The levels correspond to specific health management scenarios, operational constraints, and system requirements. Each stage also reflects analogous conditions on Earth, where similar limitations affect the delivery of medical care.

- **Level 0 (Real-time Telemedicine) - Earth Orbit (ISS / Low Earth Orbit)** Full external medical support available. Clinical tasks are guided by Earth-based experts with minimal onboard autonomy.
  - **Communication Delay:** ~0.03–0.25 s (one-way), effectively real-time.
  - **Return to Earth:** ~3-6 h (e.g., via Soyuz or Crew Dragon; emergency concepts such as UC Davis' "Space Ambulance" aim for ~4 h return capability).
  - **System Requirements:** Basic health monitoring (e.g., ECG, heart rate), minimal explainable AI support, dependence on ground control.
  - **Earth Analogue:** Urban hospital settings or intensive care units with constant expert supervision and high-bandwidth infrastructure.
- **Level 1 (Conditional Autonomy) - Moon (LOP-G / Lunar Surface)** Requires moderate onboard autonomy to bridge intermittent connections and resource constraints.
  - **Communication Delay:** ~1.2–2.6 s (one-way).
  - **Return to Earth:** ~3-5 d (depending on launch readiness and transfer trajectory).

  - **System Requirements:** Continuous wearable and behavioral monitoring, hybrid AI, basic digital twin models, asynchronous decision support, adaptive HCI for varying users.
  - **Earth Analogue:** Remote outposts, submarines, or Antarctic research stations with delayed telemedical support and non-specialist medical personnel.
- **Level 2 (High Autonomy) - Mars (Transit / Surface)**
  Autonomous health operations must compensate for extended delays and mission-critical isolation.
  - **Communication Delay:** 4–24 min (one-way), depending on the planetary alignment.
  - **Return to Earth:** 6-9 month (e.g., minimum-energy transfer), possibly >1 year if waiting for next return window.
  - **System Requirements:** Comprehensive multimodal monitoring, MGM with digital twins, advanced predictive analytics, decision support, highly contextualized HCI.
  - **Earth Analogue:** Disaster zones or warzones with disrupted infrastructure, limited staff, and time-critical care needs.
- **Level 3 (Full Autonomy) - Beyond (Deep Space Missions)**
  Complete onboard autonomy for diagnostics, interventions, and preventive care. No possibility of medical evacuation or remote assistance.
  - **Communication Delay:** Several hours to no contact, depending on location and antenna pointing (e.g., beyond Mars orbit or into interstellar space).
  - **Return to Earth:** Not possible (no feasible rescue within human lifetime or mission design).
  - **System Requirements:** Self-sufficient care: AI-supported diagnosis and intervention, robotic support, transparent models, adaptive HCI to sustain crew trust and self-efficacy.
  - **Special Case:** The enthralling and to date still visionary approach of hibernation (torpor) for the crew may require continuous AI-based vital control without human oversight [5].
  - **Earth Analogue:** Isolated elderly in rural regions or long-term care settings without specialist access, especially in crisis or climate-affected regions.

LOP-G represents a realistic near-term scenario to assess both the technological readiness and operational integration of conditional autonomy systems (Level 1). In contrast to the ISS, crew on LOP-G will periodically operate with limited external support. This creates a demand for moderate on-board decision-making capabilities and greater reliance on predictive monitoring and self-managed care. LOP-G therefore provides a crucial test environment for developing health management systems that must function under the more extreme conditions anticipated for Mars missions and beyond.

A structured continuum of situation-specific autonomy demands that health systems identify critical mission contexts, adjust operational modes, and follow predefined procedural models. These systems must remain robust and context-sensitive to enable smooth transitions between supported and fully autonomous care, especially in scenarios where evacuation is not possible and communication with Earth is delayed.

3 Technology Readiness and Open Challenges

Numerous foundational technologies for space-relevant digital health have already been demonstrated aboard the International Space Station (ISS). Wearable biosensors, including smart garments such as ESA's MagIC-Space vest, have allowed unobtrusive monitoring of

ECG, respiration, temperature, and movement during sleep without compromising astronaut comfort or mobility [8]. Radiation dosimetry has also achieved reached a high level of maturity. For example, ESA's active dosimeter continuously provides real-time data on the absorbed dose and the equivalent doses within the spacecraft [22]. Robotic systems such as Robonaut 2 have been used to explore remotely operated diagnostic procedures, including ultrasound imaging and simulated injections [20]. However, these systems remain largely disconnected. They are developed independently and tested under idealized conditions, either within the resource-rich environment of the ISS or in terrestrial contexts such as hospital settings and home care. As a result, their transferability is limited. Technologies designed for short-term clinical monitoring on Earth often perform poorly under the physiological stress, behavioral variability, and environmental constraints encountered in space or in remote terrestrial locations, such as polar research stations, disaster zones, or submarines. Three major categories of integration challenges can be identified:

- **Sensor Fusion and Environmental Validity:** Wearable, ingestible, and ambient sensors are usually validated in stable terrestrial environments. Their reliability in dynamic and extreme conditions, such as microgravity, partial gravity, or high-radiation zones, remains uncertain [21, 1]. Motion, fluid redistribution, and changes in sensor-skin adhesion may lead to physiological baseline shifts and signal artifacts. These conditions challenge conventional signal processing methods. To ensure reliable measurements throughout different mission phases, systems require redundant sensing modalities, context-aware filtering, and adaptive calibration strategies.
- **AI Maturity and Contextualization:** On Earth, AI systems increasingly support diagnostics, triage, and predictive analytics. These typically rely on large datasets from well-characterized populations. However, in space or other isolated settings, current AI applications often lack transparency, robustness, and the ability to adapt to mission-specific constraints. Most systems do not integrate knowledge of environmental stressors, resource limitations, or procedural workflows. Future architectures must combine data-driven approaches with structured evidence-based models and formal process representations to support interpretability and simulation-based decision making under uncertainty.
- **Human-System Interaction:** Usability under mission-relevant stressors, such as cognitive load, restricted mobility due to gloves or microgravity, and time-critical scenarios, has rarely been systematically studied. Many current HCI approaches follow engineering-driven designs and are not developed in collaboration with end users [17, 3]. Research shows that a lack of transparency, limited adaptability, and insufficient participatory design reduce user trust and adherence to AI-supported systems [4]. These risks are especially relevant for long-duration missions and future space tourism, where users may have limited medical training.

These open challenges require a shift in research and development strategies. Future digital health systems must be designed as cohesive and adaptive ecosystems. Rather than building isolated technical modules, developers must integrate robust sensor platforms, interpretable AI, and interaction systems that support transparent, interpretable, and user-adaptive HCI. Health autonomy should scale based on mission constraints while remaining transparent and understandable for all crew members, regardless of background or role.

Technological readiness should be evaluated not only by the existence of functional prototypes but also by integration maturity, adaptability to different mission phases, and usability under operational stress. Platforms such as the LOP-G, with intermittent communication and evolving autonomy requirements, offer a unique opportunity to test integrated systems under controlled yet realistic spaceflight conditions.

4 Co-Evolution of Monitoring, AI and HCI: Building an Integrated Digital Health Ecosystem

Digital health in space must be developed as an integrated framework. Progress in three key areas is required to support autonomous health operations during human spaceflight: continuous multimodal monitoring, structured AI, and adaptive HCI. Figure 2 presents this perspective as a modular system framework. HCI serves as a design principle that organizes the integration of enabling technologies such as multimodal sensing, interactive user interfaces, and the medical service hub with operational health contexts such as telemedical support, autonomous crew care, and smart health systems. HCI provides the conceptual basis for adaptive, interpretable, and trustworthy interaction between humans and system components. The framework allows closed-loop configurations that maintain health-related functions under varying levels of connectivity. Although bidirectional communication with Earth-based telemedical services remains possible in some scenarios, it cannot serve as a reliable baseline. The figure illustrates the need for integrated development across all components. Design decisions in sensing, inference, or interaction must reflect the requirements of each health context and support coherence throughout the framework.

To illustrate how the technological ecosystem evolves alongside mission-specific autonomy, Figure 1 also outlines selected milestones across the domains of monitoring, AI, and HCI. At Level 0, early-stage HCI interfaces serve primarily as research tools to observe crew interaction and guide future system development. On the Moon (Level 1), procedural AI guidance and initial digital astronaut models enable asynchronous decision support. Mars missions (Level 2) demand context-aware hybrid models and adaptive interfaces to support time-sensitive crew decisions without real-time supervision. Finally, deep space scenarios (Level 3) require fully integrated self-care ecosystems, including self-learning and self-correcting AI-HCI systems capable of autonomous adaptation and operational robustness in the absence of fallback options.

Multimodal Monitoring as a Basis for Context-Aware, Autonomous Health Support. Combining wearables, smart textiles, acoustic diagnostics, and external sensing technologies (e.g., radar or LIDAR) enables researchers to construct holistic context-aware health profiles [19, 2, 9]. Data quality and validity are essential, particularly in microgravity or partial gravity environments, where physiological baselines shift and sensor-skin interactions may degrade signal fidelity [21]. Adaptive calibration strategies and multimodal redundancy must therefore be integrated into system design.

Raw data must be transformed into meaningful insight through AI systems that combine real-time analytics with structured medical reasoning. Data-driven approaches, such as deep learning and generative models, are effective in identifying patterns in large and complex datasets. These must be combined with explainable AI (XAI) techniques to support trust and interpretability. In parallel, structured models are essential to represent astronaut physiology, environmental constraints, and procedural logic. Model-Guided Medicine (MGM) integrates digital patient representations, context-aware environmental models, and formal process descriptions (e.g., Bayesian networks and Business Process Modeling Notation) to generate explainable simulation-based recommendations aligned with mission protocols, while preserving critical human judgment and decision making [6, 7, 12].

HCI must Adapt to User Diversity, Cognitive States, and Mission Context. As onboard autonomy increases, astronauts must understand data and act independently. HCI systems must therefore accommodate diverse user profiles, from astronauts to scientists and space

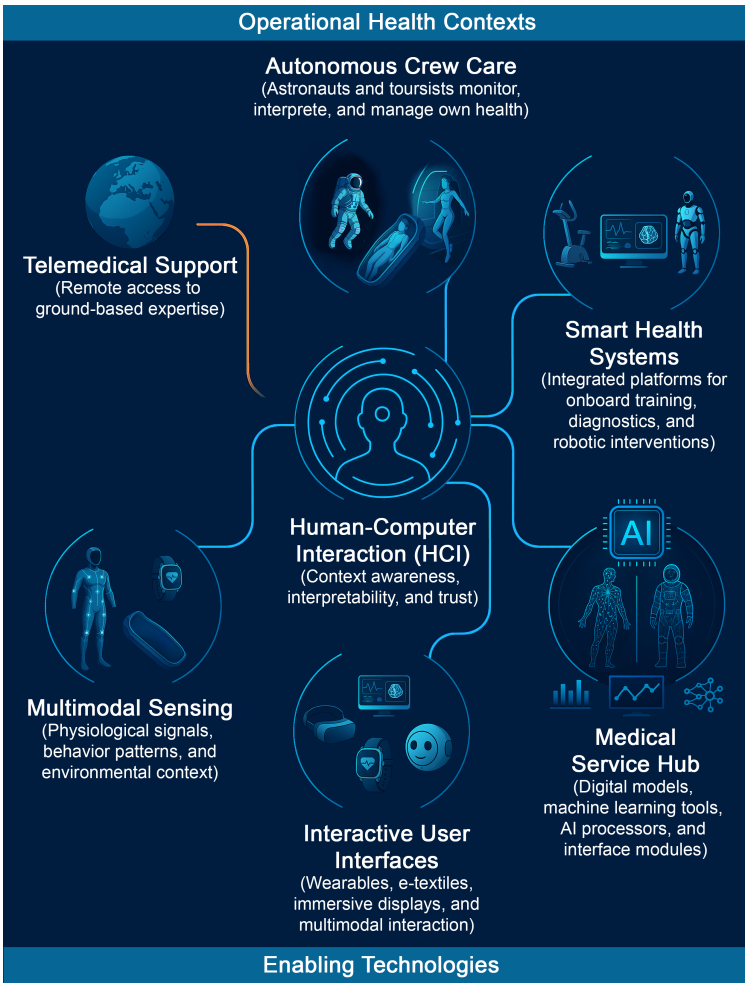

Figure 2 Conceptual architecture of a digital health ecosystem for space missions. Human-Computer Interaction (HCI) mediates between enabling technologies including multimodal sensing, interactive user interfaces, and the medical service hub, and operational health contexts such as telemedical support, autonomous crew care, and smart health systems. Because autonomy requirements shift dynamically with mission conditions, the effective development of any component requires co-design across all domains. HCI ensures consistent integration for context-aware, interpretable, and trustworthy system behavior. The framework promotes a shift from isolated solutions to synchronized and adaptive systems.

tourists, and adapt to varying cognitive states and environmental conditions. Interfaces should provide transparent feedback on system status, clearly communicate AI reasoning, and dynamically adjust to the expertise and workload of the user. Multimodal input modalities, including voice, gesture, and augmented reality overlays, are especially important where manual interaction is restricted, such as under microgravity or while wearing gloves [17, 4]. Participatory design and iterative prototyping are critical to ensure usability, safety, and long-term engagement.

Co-Design is Essential to Avoid Fragmented and Unusable Systems. Intelligent digital health systems must be developed as co-evolving ecosystems that integrate real-time monitoring, structured AI, and user-centered interfaces from the outset. Fragmented development

undermines resilience: AI models disconnected from live data lack robustness, sensors that produce uninterpretable output erode user trust, and interfaces that fail to reflect system logic compromise safety. Integrated co-design involving engineers, clinicians, AI developers, and HCI experts is essential to ensure transparency, usability, and mission readiness.

Even integrated systems are fallible. Performance depends on signal quality, mission-specific context modeling, and appropriate human interpretation. Failures can result from sensor malfunctions, poor data quality, or flawed assumptions in AI design. Systems must therefore support critical user awareness by clearly communicating uncertainties, showing confidence levels, and flagging incomplete input data. Failover mechanisms and graceful degradation strategies must be integrated to ensure mission safety even under partial system failures or degraded sensor performance. In parallel, reference models and fallback protocols provide structured responses in decision-critical scenarios, especially when autonomous behavior must remain explainable and controllable.

Embedding these safeguards into a co-design framework allows digital health systems to balance autonomy and accountability. This approach must be grounded in participatory design and iterative prototyping to ensure safety, transparency, and sustained usability across diverse missions.

5 Real-Time Learning and Training to Support Autonomous Health Decisions

Autonomous healthcare in space depends not only on technical systems but also on the crew's preparedness to understand, trust, and act upon health-related data and AI-generated recommendations. As autonomy increases with mission distance, astronauts must assume new roles as informed decision-makers, caregivers, and active participants in managing their health.

Training must Shift from Routines to Situational Health Understanding. Current astronaut training includes basic first aid and selected emergency protocols. Long-duration missions, however, require deeper comprehension of diagnostic signals, preventive measures, and procedural alternatives under resource constraints. Static instructions or video briefings are insufficient when complex procedures must be adapted to real-time crew status and evolving mission conditions. Immersive training environments using virtual or augmented reality offer scenario-based rehearsal, contextual feedback, and adaptive learning [15, 18, 16]. Training must be linked to MGM frameworks to reflect current physiological data and mission context.

Real-Time Guidance Turns Confusion into Learning and Trust. Onboard AI systems can support not only decisions but also learning by delivering contextual information, step-by-step guidance, and explanatory feedback. When sensor anomalies occur, the systems can walk users through verification steps, risk assessments, and potential actions using layered explanation interfaces. These link physiological data with expected norms and mission context, helping transform uncertainty into a learning opportunity and strengthening user competence and system trust.

Adaptive AI for Autonomous Health Decisions. Autonomous adaptation during missions is critical, as historic data may be unavailable or incomplete. Onboard AI must support "on-the-fly" learning using limited and evolving datasets. As Waisberg et al. [23] outline,

techniques such as transfer learning and synthetic data generation may enable models to adapt based on mission-specific sensor input while maintaining interpretability. Kumar et al. [14] further highlight how embedded AI systems can detect space-induced health syndromes (e.g., SANS) via onboard learning, even under strict latency and compute constraints.

Health Competence and Motivation are Key to Self-Empowered Care. Space crews are heterogeneous: scientists, operators, or future tourists may vary widely in their medical knowledge, stress response, and willingness to follow preventive protocols. Interfaces must therefore support personalized health literacy: adaptive explanations, motivational nudging, and progressive learning pathways. Behavioral modeling, when coupled with monitoring and AI analytics, can detect early signs of non-adherence and prompt corrective engagement before risks escalate. Such strategies are already explored in Earth-based care systems and are essential for maintaining preventive practices during extended missions.

Interfaces must be Designed to Teach, Not Just Inform. Training must continue throughout the mission. HCI systems should respond to user queries, guide appropriate actions, and provide clear contextualized feedback on health behaviors and outcomes. This approach supports informed action and builds the confidence needed to maintain autonomy without compromising safety or psychological resilience.

To support responsible use of autonomous health systems, training must also cultivate critical thinking. Crews must learn when to rely on AI-generated recommendations and when to challenge them, based on sensor reliability, contextual understanding, or ethical concerns. This reinforces health self-efficacy and fosters informed, autonomous decision making rather than passive acceptance.

6 Future Work: Strategic Priorities for Research and Validation

To realize the vision of autonomous, user-centered digital health systems in space, several strategic research directions must be pursued. These extend beyond individual technologies and emphasize system integration, operational realism, and ethical deployment under extreme conditions.

From Conceptual Models to Operational Systems. While this paper outlines a co-evolutionary approach combining monitoring, AI, and HCI, many proposed components, such as digital astronaut models, model-guided decision support, or adaptive interfaces, remain at the conceptual or prototypical stage. Future work must focus on the integration, testing, and validation of these systems under space-relevant constraints. The LOP-G offers an ideal near-term platform to test conditional autonomy, edge diagnostics, and context-sensitive user interfaces.

Edge AI and Robust Onboard Computing. Extended communication delays and intermittent contact require that critical health data be processed locally. Future systems must prioritize resilient, energy-efficient edge computing capable of filtering, analyzing, and contextualizing multimodal sensor streams in real time. This includes hardware robustness under radiation and power constraints, as well as software strategies for uncertainty estimation, prioritization of alerts, and fallback procedures. Recent advances in edge computing platforms show that AI-based inference can be conducted reliably under space conditions. ESA's Φ-Sat-1 demonstrated successful onboard deep learning using radiation-hardened

Myriad 2 vision processing units for real-time image filtering [10]. Similarly, Goodwill et al. [11] presented the NASA SpaceCube Edge tensor processing unit with triple-modular redundancy to ensure fault-tolerant AI processing in radiation-prone environments. These examples support the feasibility of localized health inference, anomaly detection, and fallback logic under extreme conditions.

Personalized Interfaces and Embedded Learning. As medical autonomy increases, astronauts must become both operators and learners. Interfaces must adapt to individual health literacy, stress levels, and cognitive load. Future development should focus on context-aware explanation interfaces, interactive feedback channels, and embedded training mechanisms that support decision-making without requiring constant supervision. This includes ongoing adaptation to user profiles and mission phases.

Ethical Autonomy and Trusted Decision Support. Autonomous AI systems in space must be designed for transparency, explainability, and user control. Crew members need to critically interpret AI recommendations, particularly in high-stakes scenarios without Earth-based oversight. Future work must address model limitations, error propagation, and trust calibration. Reference models, confidence estimation, and explicit communication of data quality should be standard features in decision-critical systems.

Terrestrial Translation and Dual-Use Potential. Digital health systems developed for space exploration can offer substantial benefits to Earth-based healthcare. Isolated elderly individuals, understaffed clinics, and emergency responders in remote or crisis-affected areas face comparable constraints. Future research should explore adaptation pathways, evaluate societal impact, and identify regulatory and ethical implications for dual-use deployment. Space health innovation must be understood as a catalyst, not a siloed niche.

7 Conclusion

The paper outlines a forward-looking vision for digital health in space, centered on prevention, individual empowerment, and adaptive autonomy. We introduced a structured framework of autonomy levels to demonstrate how mission distance and communication constraints shape health system requirements. Within our framework, we emphasized the co-evolution of multimodal monitoring, model-guided and explainable AI, and adaptive HCI as the foundation for context-aware and trustworthy care.

Rather than treating sensing, AI, and HCI as isolated technologies, we argue for their integrated development through user-centered design and iterative validation. Human factors, learning support, and ethical oversight are not secondary features, but essential design principles that allow autonomy without compromising safety or comprehension.

The Lunar Gateway provides a critical near-term platform to evaluate these concepts under realistic operational constraints. Insights gained from timely space missions will inform a stepwise advancement of digital health systems for more complex scenarios, including Mars transit and deep-space habitats.

Beyond their relevance for spaceflight, the digital health technologies and principles discussed here address urgent needs on Earth. Remote diagnostics, self-managed care, and adaptive AI support have the potential to transform healthcare delivery in underserved regions, during crises, and for aging populations. By investing in digital space health, we also invest in the resilience and future-readiness of healthcare on Earth.

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XR/UX for Virtual and Mixed Mock-Ups Utilization in Space Habitat Design Development: Use Cases and Lessons Learnt

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Abstract

In the frame of Artemis/Gateway programs, TASI developed in 2019 a 3D tool to support the Habitat Modules Design verification since the early phase of the design process. The aim is to improve the use of virtual mock-ups for encouraging flexible decision–making and knowledge sharing, and to reinforce fruitful interaction between the interdisciplinary teams involved in the projects. Since the virtual environment is currently not considered applicable for the HITL design developmental requirements verification phases, the lesson learnt emerged by the final users feedbacks (astronauts Samantha Cristoforetti, Luca Parmitano and Alex Gerst) during IHAB design reviews sessions in immersive environment (2019-2021) have been considered as guideline to propose a mixed reality environment able to overcome the 3D tool usability criticalities emerged. In this paper are briefly discussed the application of the VR/UX process in the frame of the crew systems design review of IHAB where the HSI requirements (e.g. anthropometrics, range of motion, orientation, clearance...) and tasks operations (e.g. galley area for dining together, four crew of 99th percentiles) have been evaluated. The comparison between the design guidelines emerged in the frame of the HITL developmental tests in a low fidelity physical mock-up performed in Turin in May 2024 and the crew feedbacks collected during the vr session in an immersive environment by using avatars, in 2021 reviewing the same crew systems are showed to be considered as additional support to reinforce the need to promote the development of virtual environments to maximize their use to support future Space Habitat Design developments. The opportunity to reduce cost/time in providing suitable verification tools like a mixed mock-up composed by simplified physical parts combined with virtual reality scenarios is under way in the frame of ERM Esprit module which will be characterize by six windows to permit the crew to observe the moon surface and take photos from the Gateway station. Testbed scenarios e.g. window scratch pane removal tasks procedures are under evaluation to test future tools combining physical infrastructures with digital set extensions supported by the XR innovative technologies under development. The main envisaged objectives go through the need to contribute to innovate processes and tools following the ongoing digital transformation in support of future habitat design development which includes lunar surface habitat (in partial gravity).

2012 ACM Subject Classification Human-centered computing

Keywords and phrases Crew Systems, User eXperience, Virtual Reality, Human System Integration, Human Centered Design, Mixed Reality, Human in the Loop

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1 Introduction

Collaborative Design is a process that brings together different ideas, roles and team members, reinforcing social relations interacting in a virtual space. This approach encourages a flexible decision-making and knowledge sharing [5]. A technical referential propose an innovative design process based on Virtual Reality technologies and User's Experience approach has been provided to be shared within the International Community in 2021 [1].



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This is based on the results achieved developing new tools enhanced through the use of virtual reality technologies [4, 2, 3] for making design assessments more effective, improve the occasion to put the physical user in the loop to obtain feedbacks and in parallel reduce the cost and the logistic complexity aiming to give a huge contribution to the feasibility to stimulate creativity through rapid prototyping, exploring interaction modalities and fostering interdisciplinary collaboration creating an inclusive environment where professionals from diverse fields, including scientists, engineers, researchers, and artists, can come together and collaborate on the design of future systems beyond the scope of traditional space systems engineering [1].

Our activities started in 2018 to put in place a design review in virtual environment supported by the HCD/ UX approach combined by VR technologies. The focus was to involve the final users since the early phase of the projects to identify habitability issues and find solutions e.g. for Crew Systems volume accommodation during the preliminary design development phases. ESA EAC VR team contributed to the 3Dtool verification providing the VPN connection within TASI, TASF and ESA EAC crew office teams which permitted the users to join together in real time from different sites in an immersive environment by using their own avatars to review the preliminary design related to the crew systems volume accommodation in IHAB where the main crew interfaces were evaluated in a low fidelity but totally "virtual" mock up.

2 VR/UX Design In Collaborative Environment Process

The Design process is based on a digital platform tool which permit to share information between engineers, designers, experts and final users in real time (in local and/or remote connection) to perform brainstorming, trade-offs, analysis and design concept reviews involving all the disciplines needed to support the activities. The team could be composed by different actors based on the applications selected and related goals. This approach will permit to collect design guidelines based on user needs, and to reduce cost/time in resolving issues and find solutions in a shared environment, enhancing cooperation within the people involved and expert's community. For Preliminary Design Review (PDR) for the International Habitat (IHAB) module for the Lunar Gateway space station, Thales Alenia Space teamed up with the European Space Agency's European Astronaut Center (EAC) to virtually review the IHAB's functional volumes and related crew accommodations. All teams involved in this virtual session, including astronauts, are preparing for life around Moon orbit by focusing on habitability requirements to enable the crew to sleep, eat, manage stowage and conduct science experiments. ESA astronauts Alexander Gerst and Luca Parmitano used their avatars to check out future habitation accommodation on Lunar Gateway | Thales Group (see figure 1).

This was made possible by a new application developed by Thales Alenia Space, called GATEWAY4U, which provides a collaborative virtual environment allowing engineers and astronauts to experience the habitat's environment during the design phase. It offers an accurate depiction of the module's architecture, layout, and functions.

Involving the crew early in the module design process enables engineers to leverage astronauts' unparalleled experience aboard the International Space Station. Their feedback will help shape upcoming design phases and support a user-centered design approach.

The tool can handle various types of information, including:

- CAD models and system structures (subsystems, equipment, etc.)
- Presentation and discussion of alternative design solutions (trade-offs)
- Identification and resolution of critical issues and conflicts



Figure 1 I-HAB Preliminary Design Review (PDR) in virtual mock up involving final users from remote.

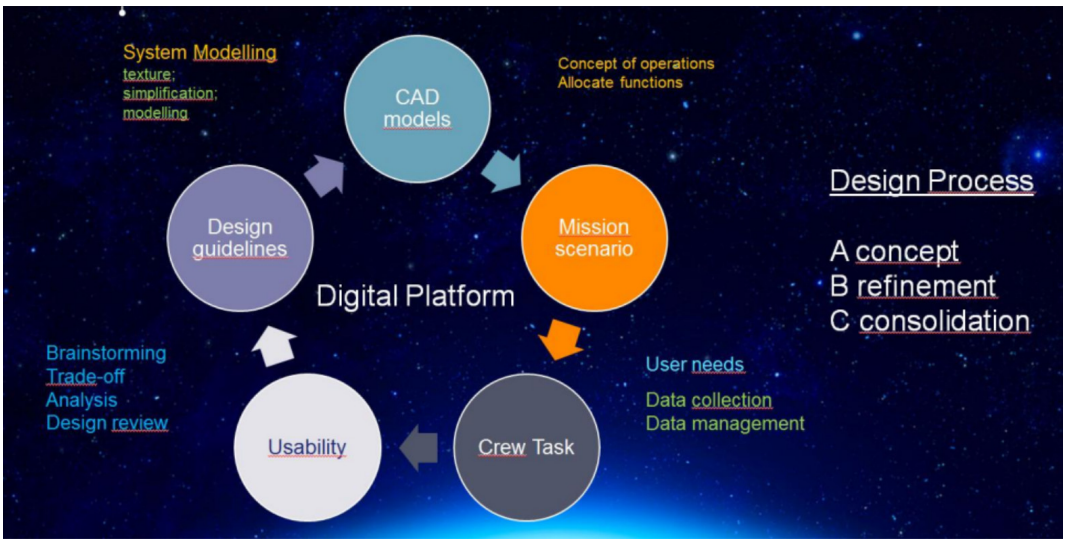

Figure 2 Design in Collaborative Environment Process Overview.

- Support for system engineering and configuration tasks in dedicated sessions
- Assistance during design development and verification phases
- Potential application for training and integration phases, and future product/service evolution

In the context of HABITAT design, the main envisaged applications are:

- Design concept review from the early stages of development
- Optimization of habitable volume
- Human factors and ergonomic analysis
- Internal architectural trade-offs

The collaborative design process is illustrated in Figures 2 and 3.

The GATEWAY4U application has undergone constant improvement since being developed. In July 2019, EAC worked with astronaut Samantha Cristoforetti in Cologne and Thales Alenia Space's teams in Turin and Cannes to conduct a collaborative session that reviewed preliminary IHAB and ESPRIT designs, as always based on a combination of virtual reality (VR) and user experience (UX). The Design process is composed by the following main steps:



Figure 3 TAS-I Gateway4U tool – VR/UX Usability Test performed in 2019 where different VR scenarios have been used (e.g. IHAB Gateway Habitat Module Crew Systems Concepts).

1. System Modelling (CAD model simplification, VR scenario definition, Mission scenario, task analysis). The VR scenario will be defined based on the mission design phases needs and the operating environment. Understanding is gained through the following activities: Develop missions and scenarios, Develop concept of operations, Allocate functions between user and system.
2. Collaborative Design (Usability Tests) The usability test are based on the active involvement of users and a clear understanding of task requirements. Users provide valuable knowledge about the context of use, the tasks, and how users are likely to work with the future product or system. Astronauts (e.g., mission specialist or payload specialist) with their extensive knowledge collected over years of experience allows for increased understanding of user needs and provide feedback on how to use the product or system. Engineering experts: ground operations personnel can interact with the final users to clarify issues and improving the understanding of proper tasks and system requirements aiming to find solutions in a more effective way.
3. Data Collection & Analysis (user's needs, design guidelines identification) The collected data will be analyzed to extract the main guidelines based on user's experience to be used in the next step of the design refinement process. Within the iterative design process described here, the evaluation activities evolve designs by identifying areas for design improvement through the gathering of quantitative and qualitative data. Evaluation of design concepts and alternatives is crucial to achieving optimal design solutions. Evaluations must begin early and continue throughout an iterative system design process. Representative users in the simulations and evaluations phases to ensure that results capture the capabilities of the user and are relatable to the mission situations.

3 Design Review in Virtual and Physical Mock-ups: Use-cases

The IHAB developmental test in virtual l mock-up performed in 2021 involving astronauts from remote in a real-time virtual session have been described in previous section. Avatars representing the users interacting in remote connection in real time are shown in Figure 1 and 3. Here below the low fidelity IHAB physical mock-up used for the developmental test performed in May 2024 is showed in Figure 4. The Galley area included a prototype of a table that has been evaluated by the test subjects of different anthropometric percentiles, that have been selected following the NASA HITL process).



Figure 4 TAS-I Gateway4U tool – VR/UX Usability Test performed in 2019 where different VR scenarios have been used (e.g. IHAB Gateway Habitat Module Crew Systems Concepts).

3.1 Use-case 1: IHAB Galley area usability and crew worksite evaluation

Four subjects of different anthropometric percentiles evaluated the usability of the volume available for dining together in the Galley area considering the accessibility to the equipment needed such as food warmer, potable water dispenser and trash bags. Dedicated R&MA (e.g., Velcro, handrail, foot restraint, etc.) items are positioned in the galley area according to the tasks/subtasks sequence.

Based on the user's feedbacks received when reviewing the design in physical mock-up in addition of the evaluation of the table overall size and height the following design guidelines have been detected: (1) remove the equipment ANITA to free up Galley space and potentially reallocate it to the multipurpose areas. (2) install four additional handrails mounted on deck side to provide secure foot restraints points during meals. (3) Study the possibility to reduce or tailor the envelope of the adjacent pump package to increase the leg space

The comparison between the Galley area operational scenarios developed in 3D environment and in physical low fidelity mock up showed in Figure 5 physical and virtual environments gives evidence that, despite of the limitations when using the digital scenario only, the user's performing the tasks in 2021 provided the same comments to orient the redesign of the Galley area, therefore, the crew since at that time, was able to perceive the issues regarding the Galley area usability issues, regarding the items and restraints accessibility, range of motion criticalities, therefore, it can be confirmed the benefits in using the virtual environments to find solutions and anticipate final users feedback as design guidelines to help engineers and designers to understand the user's needs and take them into account as early as possible to develop Space Habitat really "user" oriented.

The following two Use Cases are related to give evidence of the application of the VR/UX approach described in para 2.0. The ongoing projects are in different design developmental phases and the lesson learnt acquired in the recent past encouraged us to promote the use of the Design in Collaborative Environment process and to propose the use of a Mixed Mock-up (composed by a physical simplified parts + virtual scenarios) to review tasks operations e.g. window scratch pane removal as shown in Figure 6.

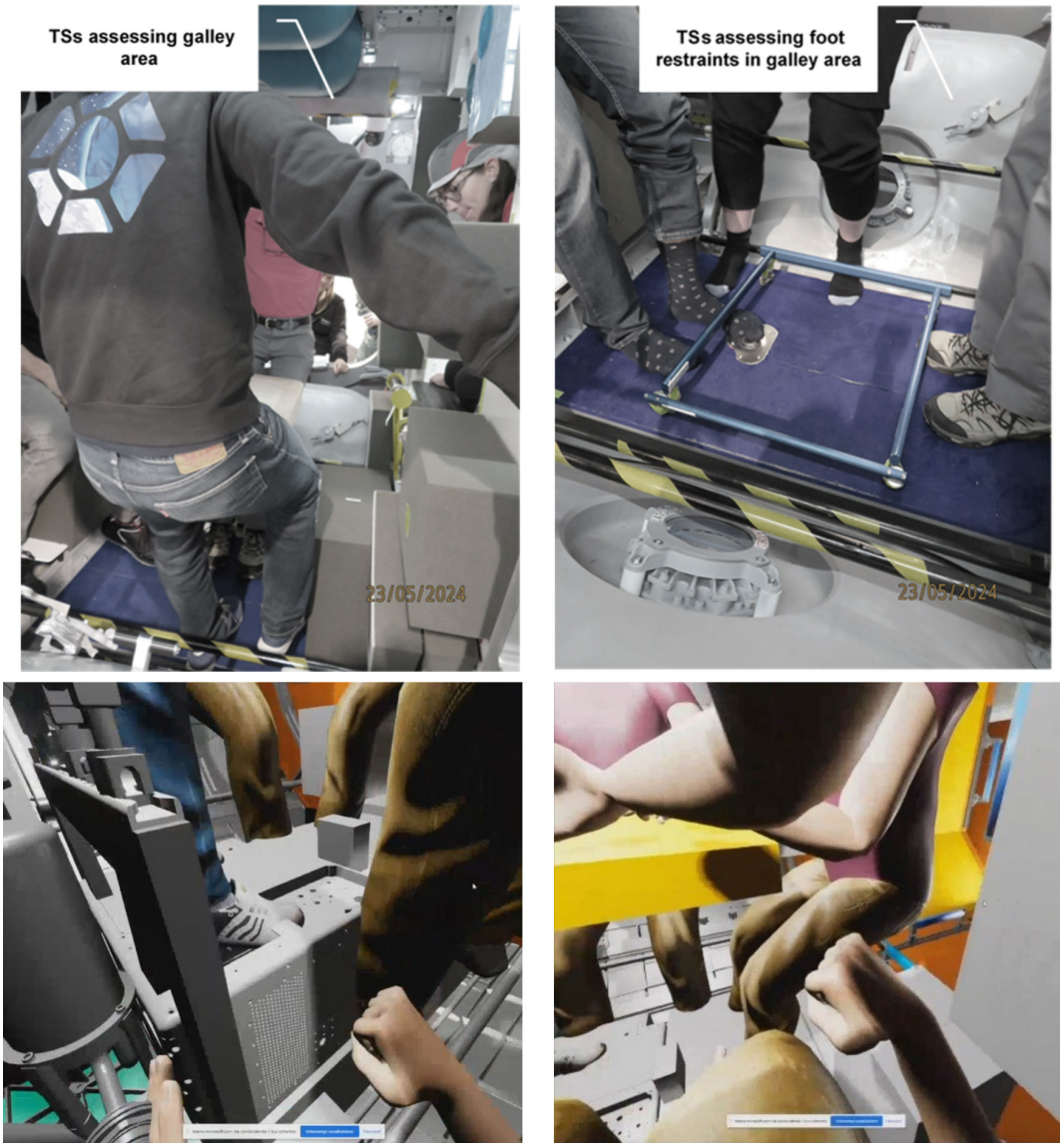

Figure 5 Comparison between physical (up) and virtual (down) environments where crew members and engineering users simulated the tasks the Galley area and a table concept to evaluate the feasibility to accommodate four crew of 99th percentiles for dinning together.



Figure 6 Scratch pane design concept under evaluation in ERM/Esprit module in Windows bay – virtual scenario with 99th mannequin simulating the neutral posture in 0g environment.

3.2 Use-case 2: ERM ESPRIT virtual mock up for window scratch pane installation simulation

For the planned HITL in low/medium mixed mock up Demo, physical parts representing the internal layout architecture of the windows bay and surrounding equipment's (e.g. handrails, CTBs) volumes to simulate the physical interference with the surrounding hardware will be provided including a scratch pane prototypes concept will be provided to review the crew tasks operations taking into account the crew needs to remove easily and little time the pane to access to the windows to take photos and observe the moon surface. This approach will permit to verify the criticalities envisaged in positioning e.g. the crew restraints and suggest design solution to fulfill the user's needs aiming to optimize the windows worksite usability from crew visibility, accessibility and operability point of views.

3.3 Use-case 3: MPH Virtual Mock-up for Hatch Opening and Closing Door's Task Simulation

In the frame of the ASI TASI NASA project MPH there is the need to review the Doors Hatch opening and closing tasks, permitted to develop IVA and EVA virtual scenarios as shown in Figure 7 to give support to the engineering team who is in charge of the design of the MPH Door and related crew I/Fs that have to be operated in a safe and easy way. Therefore, dedicated VR sessions have been put in place to apply the VR/UX approach to clarify crew usability issues handling the doors mechanisms (e.g. gearbox lever grip, shutter knob..) and evaluating the EVA restraints accommodation considering the needs to fulfill all the range of crew percentiles taking into account the peculiarity of being in a partial gravity environment.

Mockup/Simulation Description and Physical representations needed: MPH airlock volume with EVA platform & steps, EVA hatch (HF size & crew interfaces, xEVAS suit, mobility aids, xEVAs suit don/doff stands (MF volumetric), low fidelity volumetric representation of items in the airlock o virtual representations acceptable for: xEVAs UIP, airlock repress controls/displays, communications controls/displays.

To improve the realistic crew range of motion in EVA scenario the use of a dummy simulating the xEVA suit, gloves, etc. is envisaged; this to improve the human body envelope perception to understand clearance to access the crew interfaces and range of motion needed to perform EVA tasks (e.g. MPH Hatch Door's opening and closing; gearbox handle operability; EVA restraints usability, windows field of views analysis).

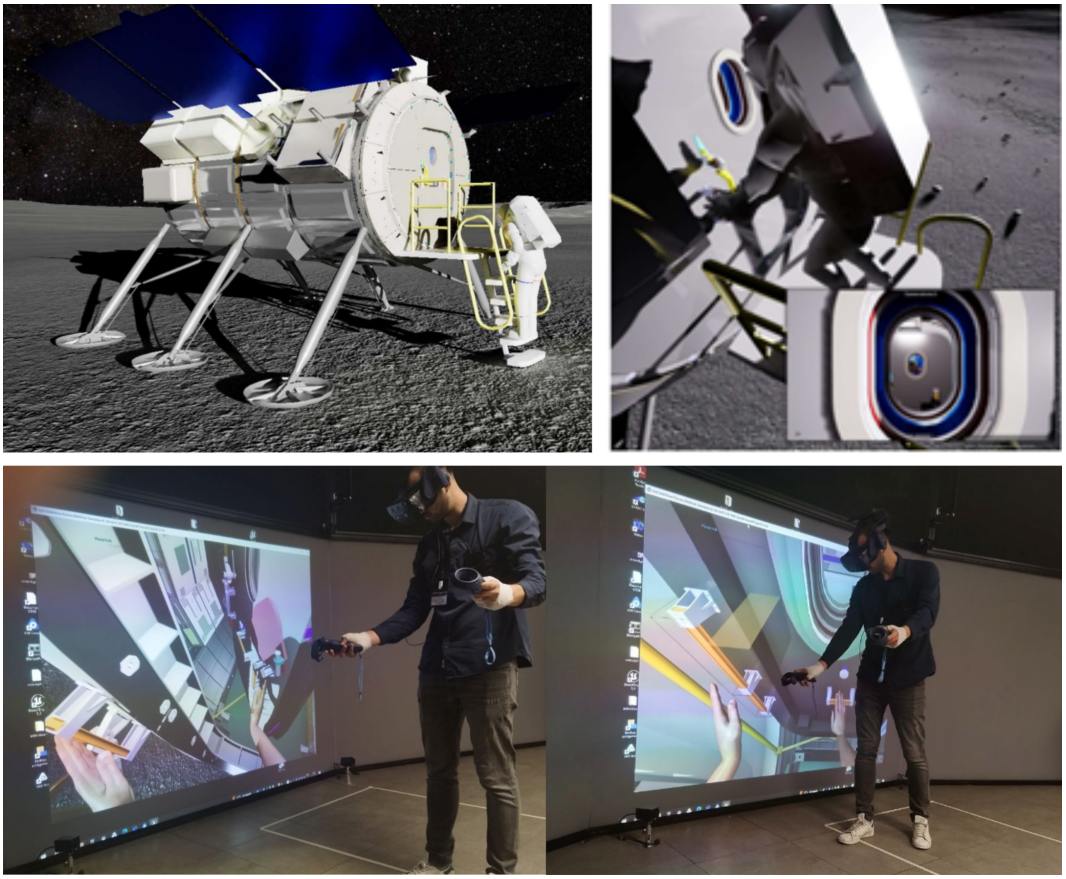

Figure 7 Left: MPH EVA Door Handrail usability test in virtual mock up in TASI VRlab. Right: MPH Doors opening and closing tasks operation. (suit and glove envelope missing) Virtual Reality Mock ups- Simulation are completely digital.

3.4 VR scenario updating

Early in the design, single-system or even single-component evaluations are performed. However, as the design matures, evaluations also mature to include entire subsystems, systems, and eventually integrated systems. High-fidelity evaluations should be conducted later in the design lifecycle.

To improve the VR scenario, the human movement's simulation and the human behavior capabilities like in absence of gravity have been implement. User's feedback has been collected to orient the avatar's functionalities upgrading: · human simulation · human interactions · features, gesture. As result, a full body avatar has been developed based on reverse kinematic applied to hands tracking in order to replicate the arm's movements. Based on the above, ergonomic and human factors analysis considering that the user can move or translate from one location to another in an "immersive" environment to review operational scenarios and crew operational needs identifying criticalities in advance and assess the system interacting in real time with other users in local or remote connections.

It is still contemplated by NASA to add, as future enhancement, Intra-Vehicular Robotics (IVR) capabilities to Gateway. Gateway remains uncrewed for much of the time and a mobile IVR device, able to translate between base points inside the cabin and between modules, is envisioned to be available for inspections and maintenance tasks and potentially working in support of crew during crewed periods. IHAB will include scarring for installation of the so called IVR homebase. The training for and use of IVR on Gateway, once it is decided to have it implemented, will form another potential application and VR use case, still to be understood in more detail.

4 Conclusions

Based on the results of the use of the VR/UX process described in para 2.0 here below are summarized some guidelines emerged during the Gateway4U tool developmental tests, which helped to clarify on how improve testbeds and verification facilities enhanced by extended reality technologies. The crew provided useful feedbacks on how to improve the 3D tool usability, clarifying the human perception issues detected evaluating the CS volumes and the human I/Fs objects interaction by using the VR functionalities available.

In the frame of Gateway Habitat Modules (e.g. IHAB, Esprit) design development reviews, in virtual and physical mock-ups, contributed to compare the usability of these verification mock ups environments and gave us additional knowledge to contribute to the transition by combining physical testbeds with digital elements, to simulate operability scenarios and find design solutions that could be achieved at a fraction of the cost of the traditional HITL process. Therefore, the next step of our activities is oriented to verify the potentiality of mixed mock-ups (composed by simplified physical parts + virtual scenarios that could be upgraded as soon the design will be more mature) to avoid the limitations detected in using virtual mock-ups only, providing new tools to be used for human systems and habitability requirements assessments:

Scheduling Design Session (SET UP)

Scheduling is fundamental. Based on the LLs acquired during the 3D tool development activities the protocols for the VR scenario set up finalization should consider the following steps: · LL1 to evaluate the efforts for the VR scenario finalization 3D models/detailed procedures) shall be provided from the involved parties at least two weeks in advance. · LL2 VR scenario shall be shared between the VR sessions participants in advance to permit corrective actions if needed. · LL3 A user manual will be provided to permit adequate

training session to the involved team. · LL4 Dedicated dry runs (1 off-line and 1 on-line) to be planned before the test to identify criticalities in advance in order to avoid misunderstanding and detect time schedule's limitation.

Proposed Roadmap for TRS updating Benefits & Limitations will be taken into account as requirements guidelines to address the next GATEWAY4U upgrading phases for: · Collisions detection features improvements · Avatar behaviors functionalities upgrading (to improve the sense of presence in VR) · Design process optimization (protocols, roles, scenarios, test procedures, questionnaires definitions. . .) · Data base collection and management Further digital tools/services linked with AR and MR applications are envisaged (e.g. design, training, support to operation, integration and testing phases).

Usability Testbed for Mixed Mock-Ups Under Development. The mixed mock-up where physical and digital mockup/simulation elements are highly integrated should be developed in the frame of the current PDR activities by TASI and tested in the frame of the ERM Esprit crew I/Fs accommodation, reviewing the worksite for each of the six Windows that will characterize this Cis Lunar Habitat. It is expected to exploit the potential to considerably enhance the validity of the future design evaluations, aiming to reach a higher level of realism and also saving time and resources in the process. In addition, the projection of visual cues into the real world could help to reduce the perception of the physical space limitations, thus increasing the user's sense of presence in the simulated environment. this approach is considered also a great opportunity to demonstrate the role of the HCD/UX methods in developing the future design verification facilities to perform HITL developmental tests.

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